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INTERPLANETARY TRAJECTORIES FOR ICE GIANT MISSION CONCEPTS

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Interplanetary Trajectory options for missions to Uranus and Neptune, launching between 2025 and 2037, are presented. Trajectories using Chemical Propulsion, Solar Electric Propulsion and Radioisotope Thermoelectric Generator Electric Propulsion, with up to four planetary flybys are investigated. The effect of different launch vehicles with or without an optimal kick stage, on flight time, inserted mass and propellant throughput, is quantified. To enable simultaneous exploration of both planets, dual-spacecraft trajectories that deliver one spacecraft to each planet from a single launch, are presented. Attractive trajectories and mission opportunities for different multi-element mission architectures are presented.

INTRODUCTION

The latest Planetary Science Decadal Survey identifies Uranus and Neptune as high priority science targets for potential future New Frontiers and flagship missions. In response, NASA initiated a one-year long study, led by JPL, to investigate potential future mission concepts. Given the open ended nature of the study objectives a broad mission-architecture trade-space exploration was performed. Possible mission architectures ranged from flyby at each planet with a planetary probe, to a flagship-level orbiter at each planet with a probe. The aim of this mission design study is to define the mission design trade-space and develop tools, techniques to identify, analyze and document high performing trajectories and map them to various mission architectures, launch vehicles.

Over the past few decades, since at least the 1960s, there have been many studies which have investigated mission design options for exploration of Uranus and Neptune.[1–7] These range from pure chemical trajectories to electric propulsion trajectories, both with and without gravity assists, with various underlying assumptions on the mission architecture.

Evaluation of concepts for Ice Giants missions began with a comprehensive assessment of feasible mission architectures. The engineering team started with an overview of possible mission design options, which were then mapped to notional flight system architectures to generate possible mission scenarios This paper is limited to the discussion on the interplanetary mission design analysis. A large set of trajectories to the Ice Giants, launching between 2025 and 2037, with a variety of launch vehicles (including NASAs Space Launch System), multiple propulsion options, and gravity assist of up to four planetary flybys, were identified and documented. Four major classes of trajectory were studied: 1) ballistic (chemical) trajectories, 2) Solar Electric Propulsion (SEP) trajectories, 3) Radioisotope Electric Propulsion (REP) trajectories, and 4) dual-spacecraft, single launch trajectories capable of delivering two spacecraft, one to each planet on a single launch. For all these, key

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Table 1. Possible mission design options

Mission Types	Max. Flybys	Primary Propulsion Type		Power (kW, 1 AU)	Max. # of Engines		DSM
		Interplanetary	*Orbit Insertion*		*EP*	*Biprop / SC*	
Chemical orbiter	4	Bi-prop	Biprop	-	2	2	Yes
Chemical orbiter + probe	4	Bi-prop	Biprop	-	2	2	Yes
Chemical flyby + probe	4	Bi-prop	Biprop	-	2	2	Yes
SEP orbiter	4	EP	Biprop	35, 25, 15	3, 2	2	No
SEP orbiter + probe	4	EP	Biprop	35, 25, 15	3, 2	2	No
Dual orbiters	4	EP	Biprop	75	26	2	No
REP orbiter	4	EP	EP/Biprop	1.65, 2.15	1	1	No

trades based on launch C3 (launch energy, km^2/s^2), flight time, delivered mass, target approach velocity, choice of gravity-assist bodies, spacecraft power, number of EP thrusters and V requirements were studied. The effect of deep space maneuvers (DSM) between flybys were also quantified. In most cases, a leveraging DSM was found to benefit mission performance by reducing flight time or launch C3, and/or by improving the phasing. Additional trades for the dual-spacecraft trajectories involved looking for hybrid trajectory pairs that would separate either directly after launch or after one of the common flybys. the role of mission architecture in determining the mission design was also examined. For example, dropping a probe from a flyby spacecraft constrains the flyby velocity due to limits on permissible acceleration that the probe can withstand.

The general solution approach consists of a broad-search followed by local pruning and optimization. An impulsive, patched-conicbased search algorithm (implemented in tool called STAR[4]), capable of adding optimal powered flybys and impulsive leveraging / deep space maneuvers between flybys,[8] was used for the initial broad search. For EP trajectories, the magnitude of the DSM was selected to reflect the maximum thrust capability of the spacecraft. Mission goals and constraints were then used to further prune the solution space. A subset of the remaining large set (which can be up to billions) of trajectories was refined using JPLs Mission Analysis Low-Thrust Optimizer (MALTO[9]), a preliminary trajectory design tool. The dual-spacecraft trajectories were identified by examining the large set of single spacecraft trajectories and adding constraints in the optimization step. Analytical and heuristic relationships were used to identify promising dual-spacecraft trajectory pairs. A new tool developed in Julia,[10] a new high-performance computing language, was used as the main driver layer for controlling execution and flow of trajectory data between STAR and MALTO.

MISSION DESIGN ARCHITECTURES

The comprehensive nature of this study resulted in a vast mission design trade space encompassing a number of mission architectures. Note, that the science team identified a planetary probe to Uranus/Neptune as one of the high priority science goals. Table 1 below lists possible mission types along with relevant mission design parameters that have been considered in this study. The above lists mission types and mission design options which were then mapped to the mission architectures to be studied with relevant constraints, as listed in Table 1. Dual orbiter and REP based mission concepts were only evaluated from a mission design perspective and did not go on to point design Team-X[11] study. Various limits, as defined in Table 1, are result of discussions with the science and

Table 2. Trajectory broad-search mission parameters and limits

#	Mission Options	Payload Mass (kg)	Max. Cruise TOF (yrs.)	Max. OI-DV (km/s)
1	Uranus orbiter with SEP stage + probe	50	12	4.5
2	Uranus orbiter with SEP stage	150	12	4.5
3	Neptune orbiter with SEP stage + probe	50	13	4.5
4	Uranus flyby + probe	50	12	-
5	Uranus orbiter + probe	50	12	2
6	Uranus orbiter	150	12	2

Table 3. Launch vehicle options

Launch Vehicle Type	Max. Launch C3 (km2/s2)		Adapter Type	Fairing Dia. (m)
	Nominal	*With Optimal Kick Stage*		
Atlas V (551)	60	225	C22 adapter	5
Delta-IV Heavy	100	225	1575-5 payload attach fitting	5
SLS Block 1-B	135	225	Notional (assumed to be included in LV performance)	8.3

engineering team. Using these parameters and the assumptions listed in Table 2, a broad interplanetary trajectory search was carried out.

ASSUMPTIONS

Launch Vehicle Assumptions

Table 3 lists performance limits and launch fairing characteristics of the three different launch vehicles considered in this study. Performance improvement to each of the three launch vehicles using an optimal kick stage was also computed. The optimal kick stage fuel load optimization was carried using a brute force maximization procedure. Figure 1 shows the nominal and optimal kick stage-assisted performance for each of the three launch vehicles. Given a kick-stage ISP, Propellant Mass Fraction (PMF) and burn altitude the kick-stage propellant load is optimally chosen to maximize delivered payload mass for a given launch C3. The optimal kick stage enables high C3 launch (¿100 km2/s2) and increases payload mass capability. Note that kick-stage does not help with low C3 launches. In fact, the kick-stage selection algorithm (developed for this study) chooses zero kick-stage propellant mass for the low C3 case, thereby eliminating the need to have a kick-stage.

Propulsion Assumptions

Chemical Propulsion: All mission options discussed in this study assume that the spacecraft carries a monopropellant system for small maneuvers and attitude control. Furthermore, mission options which go into orbit around Uranus or Neptune also carry a high performance bi-propellant system (with 325 sec ISP). As listed in Table 2 a maximum orbit insertion ΔV constraint of 4.5 km/s was imposed to keep the propulsion subsystem in a reasonable performance range. The chemical propulsion system was assumed to be consisting of two Aerojet 890N engines (R-42DM).

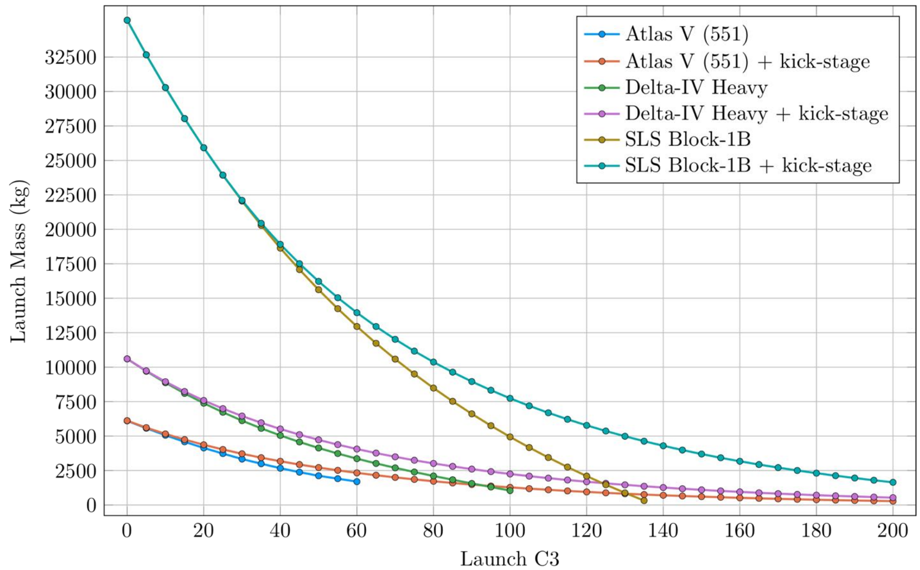

Figure 1. Launch vehicles performance design space

Table 4. SEP stage assumptions for various configurations

Target Planet	# of Ion Engines	Solar Power at 1 AU (kW)	Allowable Propellant Throughput (kg)	SEP Stage Dry Mass (kg)
Uranus	2	15, 25	1300, 1300	600, 700
Uranus	3	35	1950	1000
Neptune	2	15	1300	600
Neptune	3	25, 35	1950, 1950	800, 1000

Solar Electric Propulsion (SEP): Some mission options listed in Table 2 utilize a solar electric propulsion (SEP) stage in the inner solar system to increase delivered mass to the target planet. Trajectories making use of a SEP stage are very sensitive to the stage dry mass; which is dropped off before planetary orbit insertion. The SEP stage mass (crudely) depends on number of ion engines, solar array size (or power at 1AU) and required propellant throughput.

Table 4 lists various assumptions made during the SEP trajectory broad search. Some of these assumptions (e.g. SEP stage dry mass), which were based on previous studies, turned out to be somewhat optimistic when assessed by JPL Team-X, however they do serve to capture what-if scenarios which could be realized with technology advancements in lightweight structures and propellant tanks.

Radioisotope Electric Propulsion (REP): The current study also looked at radioisotope electric propulsion (REP) trajectories powered by the radioisotope thermoelectric generators or RTGs. The spacecraft was still assumed to have a bipropellant propulsion system for orbit insertion at the target planet. The notional REP system was assumed to be part of the core spacecraft (consisting of XIPS ion thrusters[12]) and not dropped before orbit insertion. Trajectories were optimized to pick the optimum ratio between orbit insertion propellant usage and REP xenon usage. Specifically,

Table 5. REP stage assumptions for various configurations

Target Planet	# of Ion Engines	REP Power (kW)	Allowable Propellant Throughput (kg)	Maximum Cruise Time (yrs.)
Uranus	1+1	1.65, 2.15	1103, 820	12
Neptune	1+1	1.65, 2.15	1103, 820	13

the mission design trade-space analysis considered potential advanced RTG (SMRTGs *) powered trajectories bellowing under the following assumptions (Table 5). REP trajectory options were evaluated assuming a launch with either the Atlas V (551) or the Delta-IV Heavy launch vehicle.

MISSION DESIGN TRADE-SPACE

In this section, we summarize the results of a broad search of trajectories to Uranus and Neptune launching between the year 2025 and 2037. The maximum flight time for a mission to Uranus was set to 12 years (see Table 2) and for Neptune was set to 13 years. Along with all-chemical propulsion trajectories, three different SEP power levels + engine configurations were considered. See Table 1 and Table 4 for different configuration options. Two mass metrics are defined for concise presentation of results in this section:

$$\textbf{Arrival Mass}\text{ (kg) = Launch Mass - Interplanetary Propellant Mass} \quad (1)$$

$$\textbf{Useful Inserted Mass}\text{ (kg) = Arrival Mass - (1+TMF)Orbit Insertion Propellant Mass} \quad (2)$$

where the interplanetary propellant mass can be either bipropellant or xenon mass (or both) consumed during the interplanetary cruise phase of the mission. TMF stands for Tank Mass Fraction of the Bi-propellant tanks, used for orbit insertion. A constant TMF of 0.1 was assumed for this trade study. The capture orbit assumes an orbit insertion maneuver at a periapsis of 1.05 Planet Radii. This helps in avoiding rings at both Uranus, Neptune and reduces the orbit insertion ΔV. For consistency, the capture orbit period was fixed to 120 days during the broad search. More details on orbit insertion is discussed in the next section.

Uranus and Neptune Orbit Insertion Considerations

Orbit insertion at Uranus and Neptune is challenging and is influenced by following factors:

1. **Arrival velocity:** The interplanetary flight time limits results in high arrival velocities (V_∞) at Uranus and Neptune. For a given flight time, the arrival V_∞ is generally higher for Neptune as it is further away from the Sun.
2. **Gravity well:** Uranus and Neptune have a smaller gravity well compared to Jupiter or Saturn, this reduces the "Oberth Effect" leading to higher orbit insertion ΔV.
3. **Ring avoidance:** Spacecraft entering orbit around Uranus and Neptune need to avoid the rings during plane crossing.

Coupling of these effects results in a large orbit insertion ΔV. Figure 2 and 3 show orbit insertion ΔV as a function of arrival V_∞ at both planets, respectively. For consistency, an insertion orbit

*http://www.lpi.usra.edu/opag/meetings/feb2016/posters/3-GPHS-RTG.PDF period of 200 days is assumed for these figures. The colored legend represents orbit insertion periapsis in units of planet radii. The Neptune gravity well is stronger than Uranus by $\sim 18\%$, hence for the same arrival V_∞ and periapsis radius, orbit insertion ΔV is smaller than that for Uranus.

The science team decided that to ensure a safe orbit insertion (avoiding rings) at either planet,

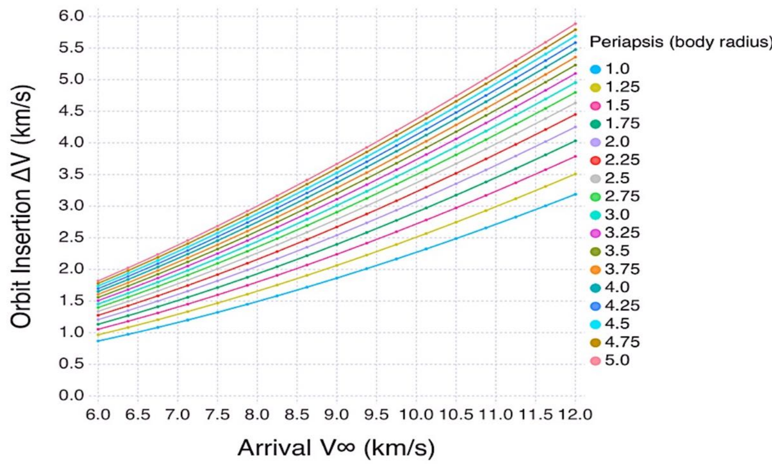

Figure 2. Arrival V_∞ vs. Uranus Orbit Insertion ΔV

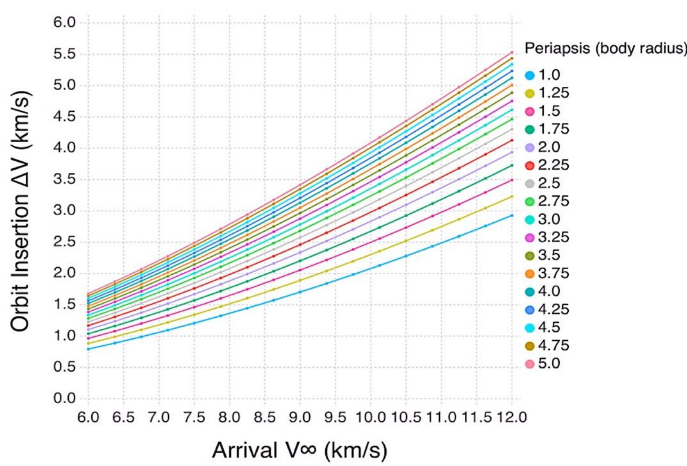

Figure 3. Arrival V_∞ vs. Neptune Orbit Insertion ΔV

the ring plane crossing should be either at ≤ 1.08 body radii or at ≥ 1.25 body radii. To reduce orbit insertion ΔV the mission design team decided on an orbit insertion with a minimum periapsis radius of 1.05body radii at both planets. For the mission options considered in this study, orbit insertion ΔV at Uranus ranged from 1.7 km/s to 2.5 km/s and for Neptune it ranged from 2.3 km/s to 3.5 km/s.

Planetary Probe Considerations

Some of the mission concepts considered in Table 2 had an atmospheric probe (for Uranus or Neptune). After a back-of-the envelop study on orbiter divert maneuver ΔV requirements, the probe trajectory was fixed to have a coast of 60 days, before atmospheric entry, at either of the planets. The probe entry was in the same direction of motion as the spacecraft. This approach is similar to that adopted by the Galileo probe and the Huygens probe. This standard hyperbolic probe entry at either of the planets must trade the following design parameters:

1. Orbit insertion ΔV magnitude
2. Probe g-load tolerance
3. Probe-orbiter relay telecommunications requirements (aspect angle and range); related to the probe Entry Flight Path Angle (EFPA)

Orbit insertion ΔV is sensitive to the periapsis altitude (see previous section). Higher orbiter insertion periapsis provides better probe-spacecraft data rate, relay line-of-sight and longer persistence (lower angular rate relative to probe), but results in larger orbit insertion ΔV. Shallow EFPA reduces probe g-load, but presents challenging relay geometry and increases cumulative probe heat load. The EFPA for a Uranus and Neptune probe were carefully selected to balance probe-orbiter relay geometry, probe heat/entry g loads, time between probe entry, and orbit insertion ΔV. Increasing the separation increases the range between orbiter and probe while decreasing this separation puts pressure on mission operations for performing two mission critical events (probe entry and orbit insertion) within a short time. During the design studies, it was found that a 2-hour gap between probe atmospheric entry (assumed to occur at $\sim$1,000 km altitude) and orbit insertion would suffice for both Uranus and Neptune. This resulted in safe EFPA of -30 degrees for Uranus and -20 degrees for Neptune. The probe entry analysis was carried out by NASA Ames research center and further discussion of those results are out of context of this paper.

Chemical Mission Options to Uranus

Figure 4 highlights the interplanetary trajectory options for a chemical mission to Uranus with up to 4 flybys. The trajectories were optimized for one year launch window bounds. The Atlas V (551) launch vehicle option allows for $\geq$4,000 kg arrival mass at Uranus and $\geq$1,600 kg of mass into orbit around Uranus with $\sim$11-year interplanetary cruise time. Using the Delta-IV Heavy results in $\geq$2,000 kg mass in Uranus orbit in $\sim$10 years from launch. Launching on an SLS, we see a dramatic increase in the useful inserted mass at Uranus ($\geq$10,000 kg for 11-year flight time). Using SLS it is also possible to insert $\geq$2,000 kg in Uranus orbit in $\sim$8 years from launch. The limiting factor here is the maximum allowable orbit insertion DV of 4.5 km/s (see Table 2), which in turn limits the arrival V_∞ at Uranus.

Figure 5 lists all possible launch opportunities between 2025 and 2037. There is a clear optimal launch period between 2030 and 2034. This corresponds with the availability of a Jupiter gravity assist. High-performing launch opportunities are similar across the three launch vehicle options. The next few sections summarize the trade-space of trajectories to Uranus and Neptune.

Chemical Mission Options to Neptune

Figure 6 highlights the interplanetary trajectory tradespace for a chemical mission to Neptune with up to 4 flybys. Given that Neptune is further out in the solar system, the Atlas V (551) launch vehicle option allows only for $\geq$3000 kg arrival mass at Neptune and $\geq$800 kg of mass into orbit around Neptune with $\sim$13-year interplanetary cruise time. The low inserted mass is due to high relative velocity at Neptune and larger launch C3 requirements. Using the Delta-IV Heavy launch vehicle results in ≥1,500 kg mass in Neptune orbit in ∼13 years from launch. Launching on an SLS, we again see a dramatic increase in useful inserted mass at Neptune (≥5,000 kg for 13-year flight time). Using SLS it is also possible to insert ≥1,700 kg in Neptune orbit in ∼11 years from launch. The limiting factor (more so for Neptune) is again the maximum allowable orbit insertion DV of 4.5 km/s, which in turn limits the arrival velocity at Neptune.

Figure 7 lists all possible launch opportunities between 2025 and 2037. There is a clear optimal launch period between 2030 and 2034. This corresponds with the availability of a Jupiter flyby. High-performing launch opportunities are similar across the three launch vehicle options.

SEP Mission Options to Uranus

Using Atlas V (551) LV: Figure 8 highlights the interplanetary trajectory tradespace for SEP missions to Uranus with up to 4 flybys, launching on Atlas V 551 and with three different SEP power levels (15 kW, 25 kW and 35 kW). The three SEP power levels result in different SEP stage dry mass and number of engines as shown in Table 4. Using the 15 kW SEP stage, we get ∼4,000 kg arrival mass at Uranus in ∼9 years from launch. The maximum arrival mass of ∼4,900 kg is possible for a 12years trajectory. Going to high power levels gives us no benefit in terms for arrival mass when launching on the Atlas V 551 as the trajectory performance is limited by launch C3 and number of SEP engines (maximum thrust). A similar trend is noted for the useful inserted mass metric. A 15 kW SEP stage trajectory allows for ≥2000 kg mass in to Uranus orbit in ∼10 years from launch and this trend remains more or less the same for higher SEP power levels. There appears to be a sweet spot SEP power level between 15 kW and 25 kW and it is recommended that this be further investigated in a follow up study. Please note that these results are only valid for assumptions listed in Table 4. If the SEP stage is considerably heavier than assumed in Table 4the sweet spot SEP power will shift towards higher power levels of 25 kW. Furthermore, going to a heavier SEP stage will resulted longer interplanetary flight times. See later sections for more details.

Using Delta-IV Heavy LV: Figure 9 highlights the interplanetary trajectory tradespace for SEP missions to Uranus with up to 4 flybys, launching on the Delta-IV Heavy launch vehicle. The performance trends remain similar and with the exception that going to higher power levels results in slight improvement in useful inserted mass. A 15 kW SEP stage trajectory allows for ≥2,000 kg mass in to Uranus orbit in ∼9 years from launch. For higher power levels, we see a steady reduction in flight time for same mass in Uranus orbit. A 15 kW SEP stage can deliver in excess of 3,000 kg in Uranus orbit in 10years and going to a 35 kW SEP stages increases the inserted mass to almost 4,000 kg. As noted before, going to a heavier SEP stage results in longer interplanetary flight times, which was the case during the first two Uranus Team-X studies.

Using SLS-1B LV: Figure 10 highlights the interplanetary trajectory tradespace for SEP missions to Uranus with up to 4 flybys, launching on the SLS-Block 1b launch vehicle. SLS provides a dramatic improvement in inserted mass or reduction on flight time at all power levels. The performance trends between the three SEP power levels is more pronounced. Going to higher SEP power levels results in improvement in both arrival mass and useful inserted mass. A 15 kW SEP stage trajectory allows for ≥2,000 kg mass in to Uranus orbit in ∼7 years from launch. For a fixed 2,000 kg useful inserted mass we dont see significant reduction in flight time from going to high power levels. This is due to the fact that we are hitting the orbit insertion DV limit of 4.5 km/s. On the other hand, a 15 kW SEP stage can deliver in excess of 8,000 kg in Uranus orbit in 11 years and going to a 35 kW SEP stages increases the inserted mass to ≥9,000 kg for the same 11 years cruise time.

Uranus SEP Launch Opportunities: Figure 11 lists all possible launch opportunities between 2025 and 2037. Only the 25 kW case, for each LV, is shown as the trend remains the same across different SEP power levels. The optimal launch period is between 2030 and 2034 but off-nominal dates are also performant. High performance launch opportunities perform similarly across the three launch vehicle options.

SEP Mission Options to Neptune

Using Atlas V (551) LV: Figure 12 highlights the interplanetary trajectory tradespace for SEP missions to Neptune with up to 4 flybys, launching on Atlas V (551) and with three different SEP power levels (15 kW, 25 kW and 35 kW). The three SEP power levels result in different SEP stage dry mass, total propellant throughput and number of engines, as shown in Table 4 Using the 15 kW SEP stage, we get $\geq$4,000 kg arrival mass at Neptune in $\sim$12 years from launch. The maximum arrival mass of $\sim$4,700 kg is possible for a 13 years trajectory. Going to high power levels gives some benefit in terms of arrival mass when launching on the Atlas V 551 as the trajectory performance is limited by launch C3 and number of SEP engines (maximum thrust). A similar trend is noted for the useful inserted mass metric. A 15 kW SEP stage trajectory allows for only $\sim$1,200 kg mass in to Neptune orbit for a $\sim$13-year interplanetary trajectory and going to higher power levels doesnt show significant benefit. Please note these results are valid for assumptions listed in Table 4. If the SEP stage is considerably heavier than assumed, the sweet spot SEP power will shift from 15kW towards higher power levels of 25 kW. Furthermore, going to a heavier SEP stage will result in longer interplanetary flight times, as was observed during the Neptune mission Team X session.

Using Delta-IV Heavy LV: Figure 13highlights the interplanetary trajectory tradespace for SEP missions to Neptune with up to 4 flybys, launching on the Delta-IV Heavy launch vehicle. The performance trends remain similar and with the exception that going to higher power levels results in some improvement in arrival and useful inserted mass. A 15 kW SEP stage trajectory allows for $\geq$2,000 kg mass in Neptune orbit for a $\sim$13 years interplanetary trajectory. For higher power levels, we see a small but steady increase in useful inserted mass for the same 13-year interplanetary flight time.

Using SLS-1B LV: Figure 14 highlights the interplanetary trajectory tradespace for SEP missions to Neptune with up to 4 flybys, launching on the SLS-Block 1b launch vehicle. As for Uranus, SLS provides a dramatic improvement in inserted mass or reduction on flight time at all power level. Going to higher SEP power levels results in improvement in both arrival mass, useful inserted mass. A 15kW SEP stage trajectory allows for $\geq$2,000 kg mass in to Neptune orbit in $\sim$11.5 years from launch. For a fixed 2,000 kg, useful inserted mass, we see a significant reduction in flight time when we go to high SEP power levels. A 35 kW SEP trajectory, launched on an optimal date, requires only $\sim$10 years to insert $\sim$2,000 kg of mass in to Neptune orbit. This is due to the fact that SLS has better upper stage performance at lower C3s and the bigger SEP stages makes up for the loss in launch energy. One other hand a 15 kW SEP stage can deliver in excess of 4,000 kg in Neptune orbit in 13 years and going to a 35 kW SEP stages increases the inserted mass to $\geq$5000 kg for the same 13 years cruise time. As noted before, going to heavier SEP stage results in longer interplanetary flight times and larger SEP propellant usage.

Neptune SEP Launch Opportunities: Figure 15 lists all possible launch opportunities to Neptune between 2025 and 2037. Only the 25 kW case is shown as the trend remains the same across different SEP power levels. The optimal launch period is between 2029 and 2031 but off nominal dates are also performant. The optimal launch period signifies the availability of Jupiter flyby. High performance launch opportunities perform similarly across the three launch vehicle options.

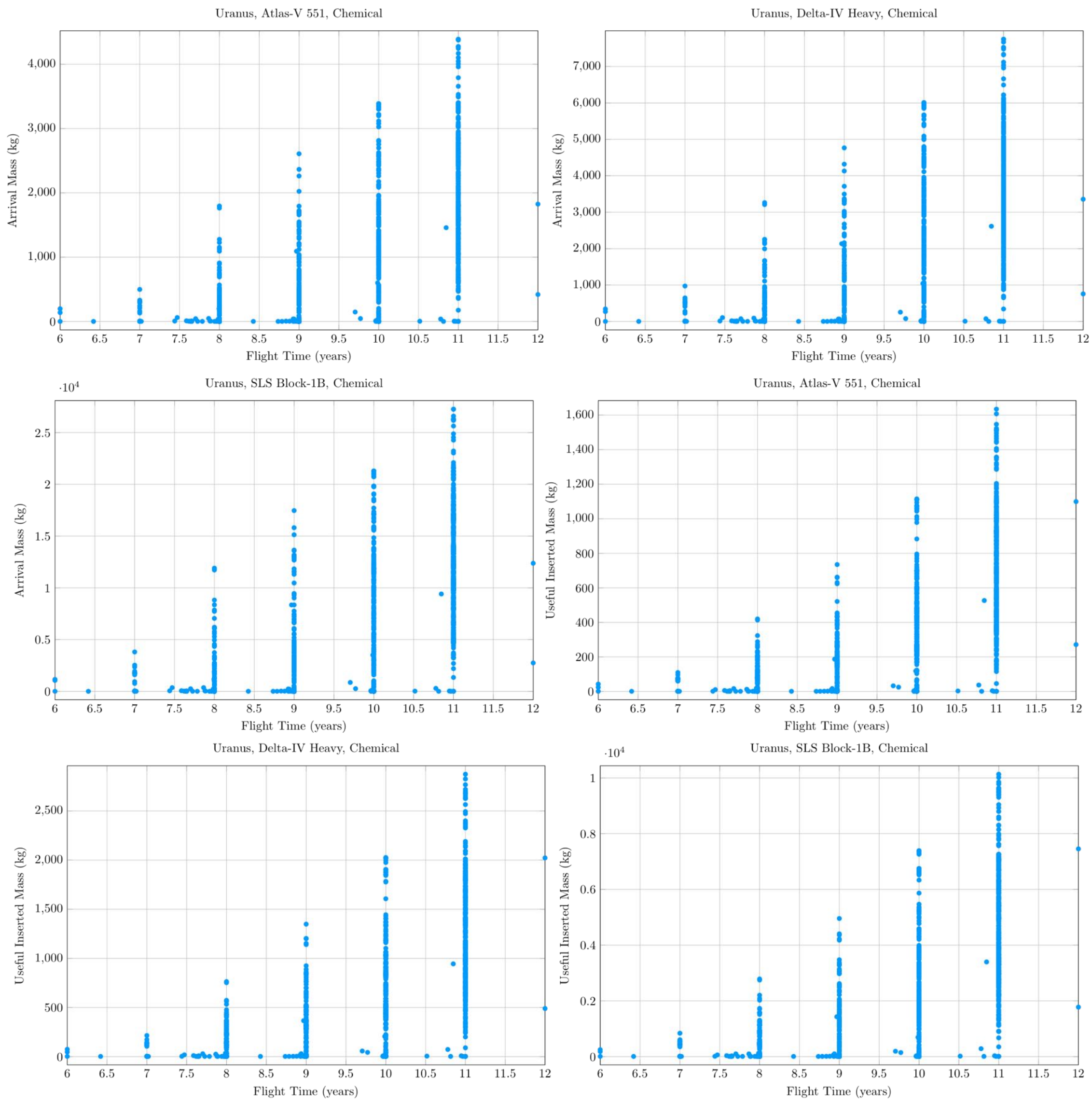

Figure 4. Chemical trajectory options to Uranus: arrival and useful inserted mass

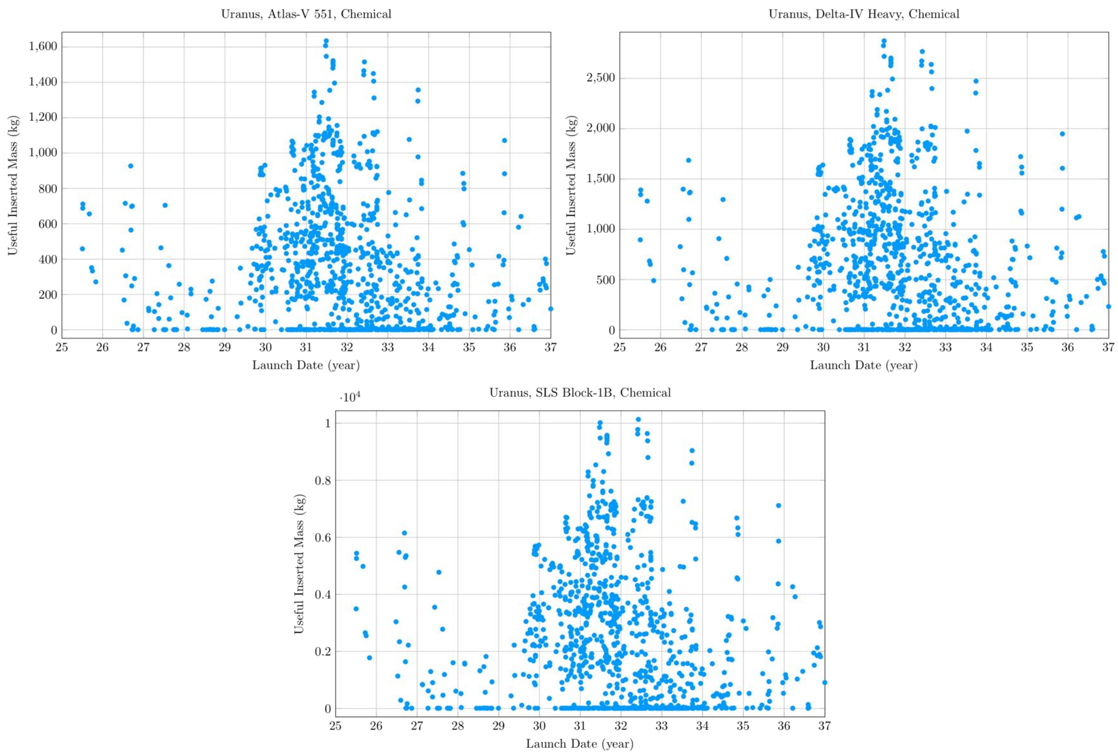

Figure 5. Chemical trajectory options to Uranus: launch opportunities

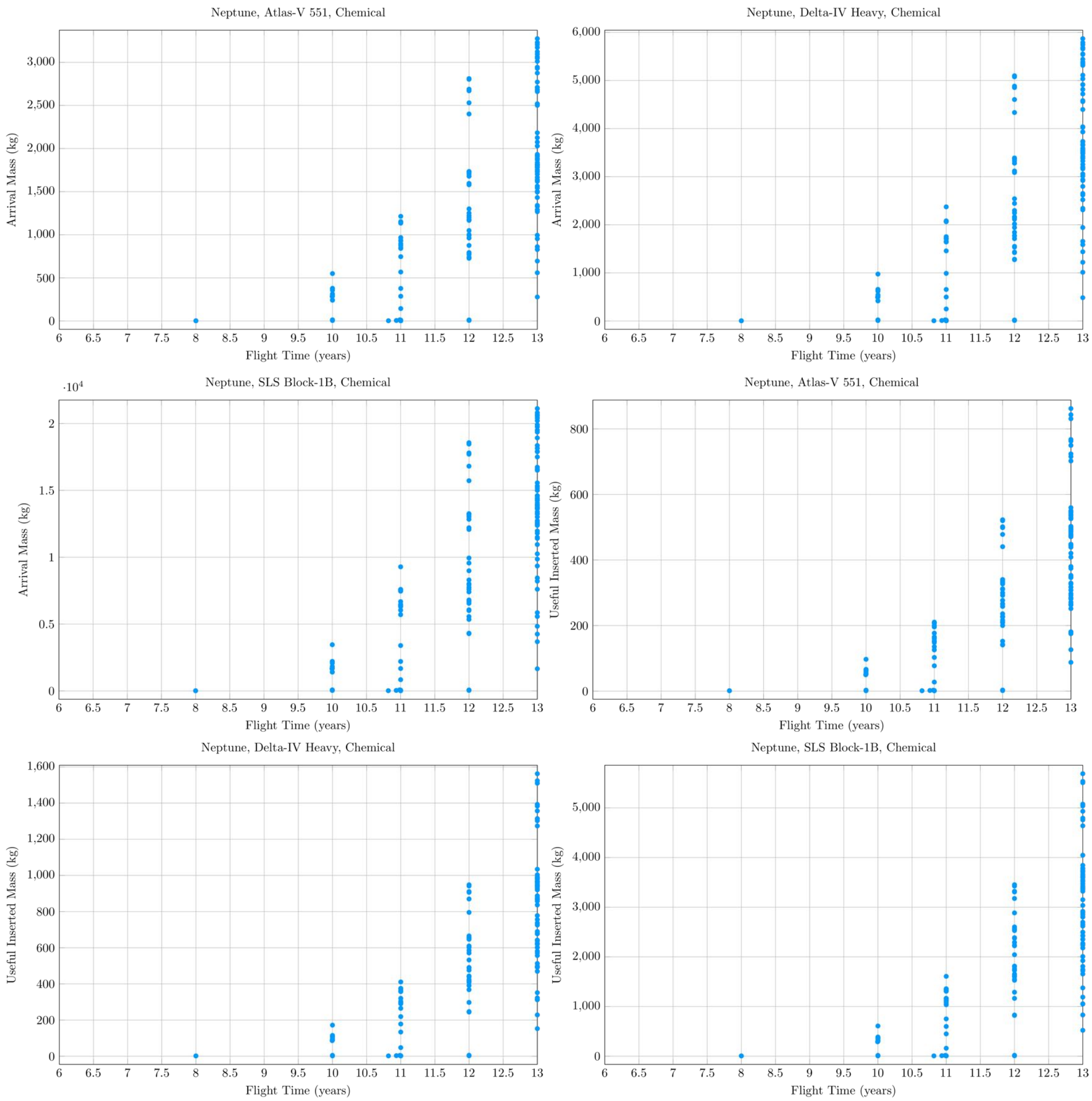

Figure 6. Chemical trajectory options to Neptune: arrival and useful inserted mass

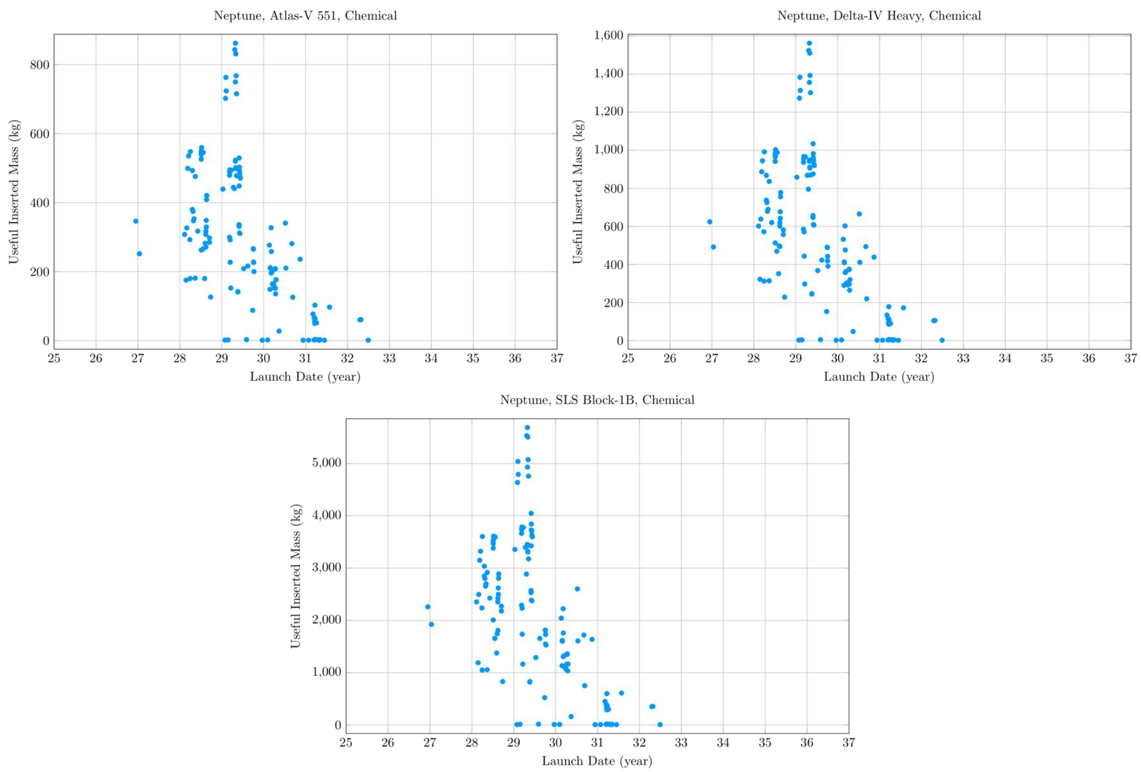

Figure 7. Chemical trajectory options to Neptune: launch opportunities

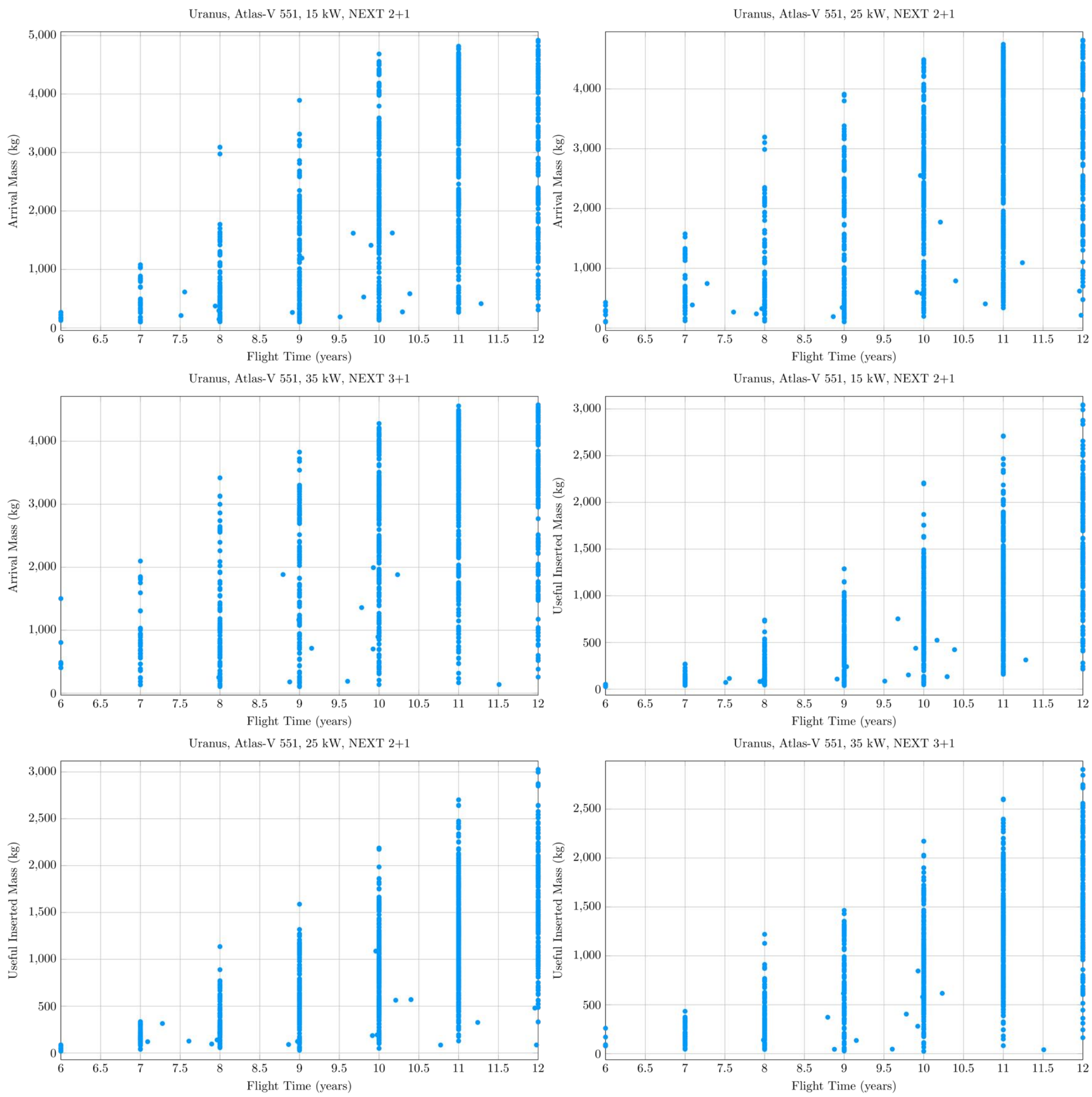

Figure 8. SEP trajectories to Uranus: Atlas V (551) with 15 kW, 25 kW and 35 kW SEP power

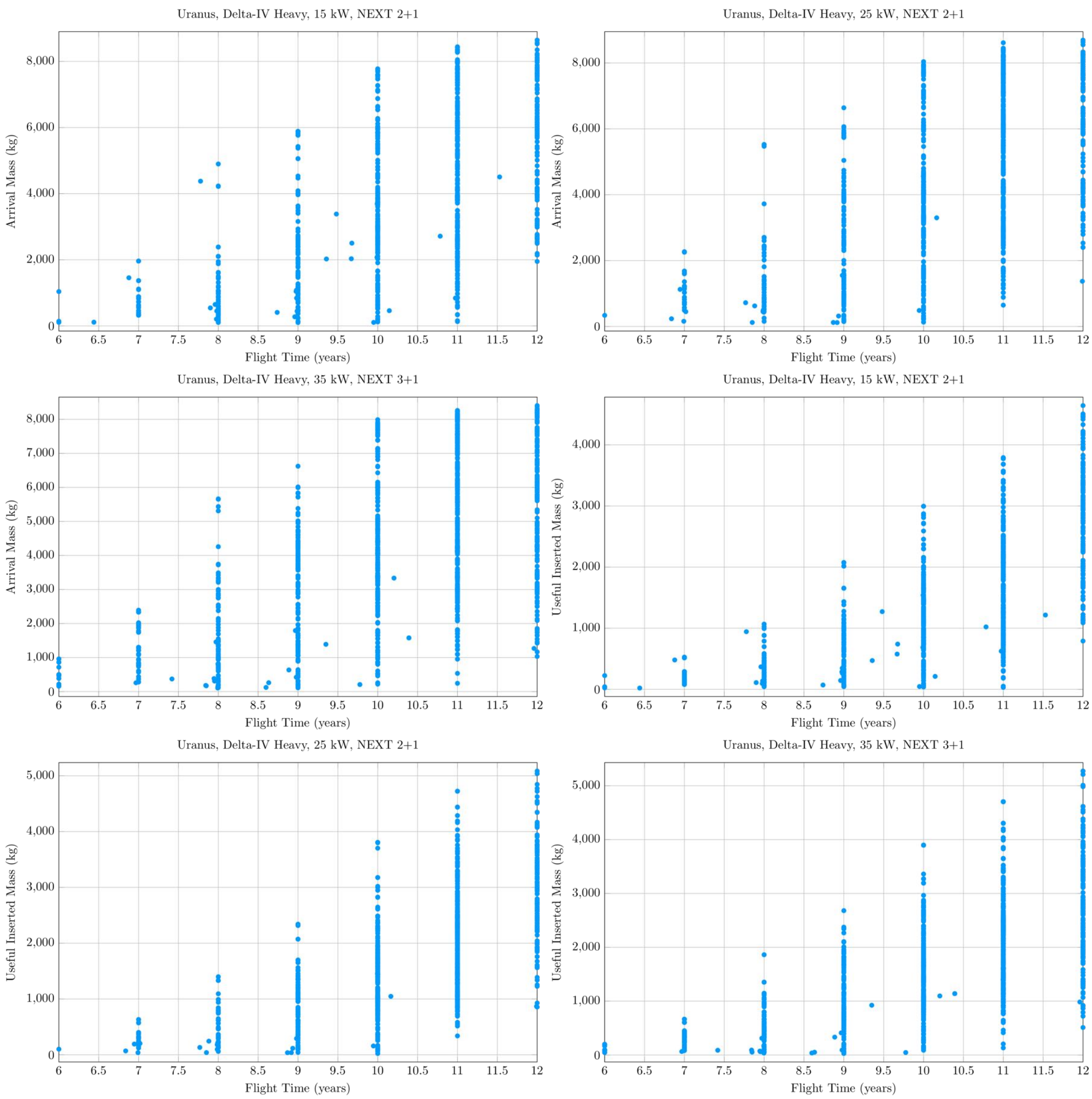

Figure 9. SEP trajectories to Uranus: Delta-IV Heavy with 15 kW, 25 kW and 35 kW SEP power

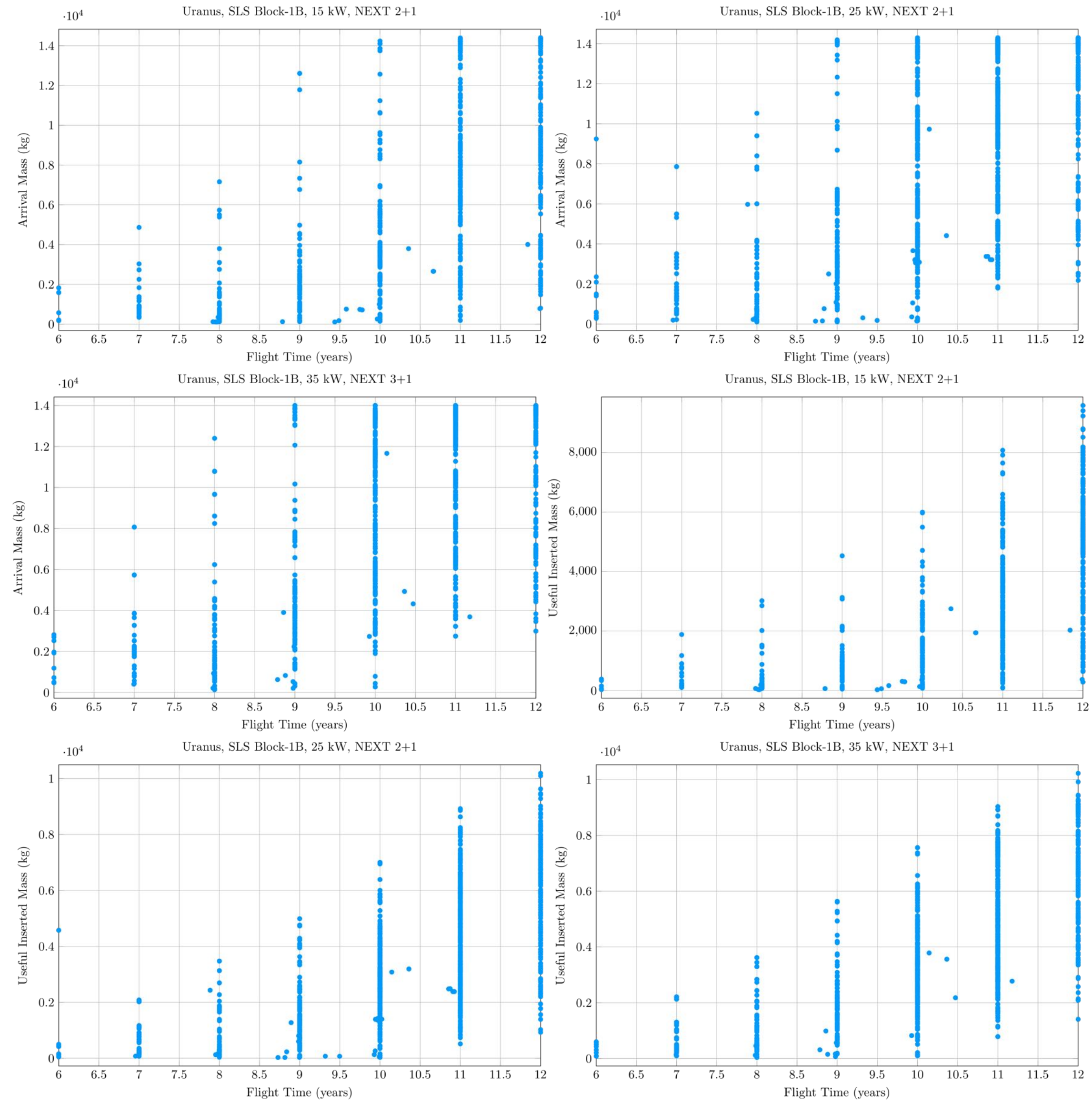

Figure 10. SEP Trajectories to Uranus: SLS Block-1B with 15 kW, 25 kW and 35 kW SEP power

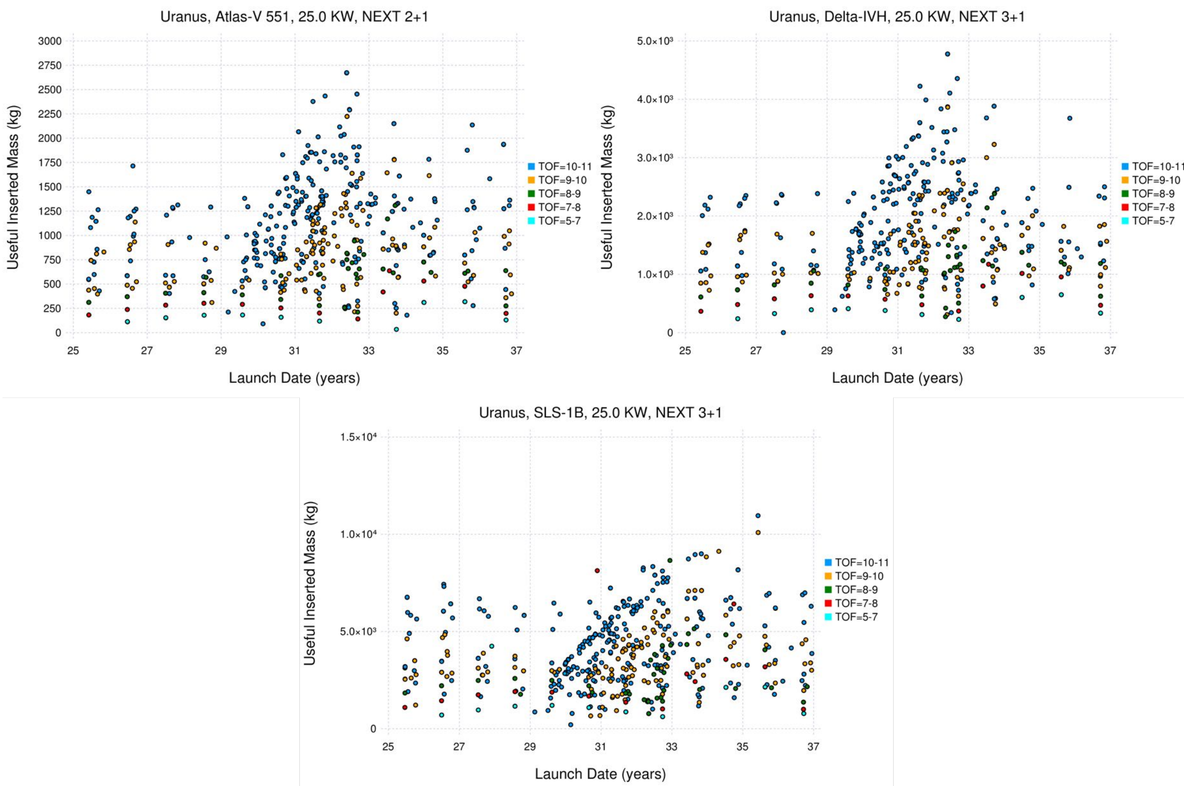

Figure 11. SEP trajectory options to Uranus: launch opportunities for 25 kW SEP power case

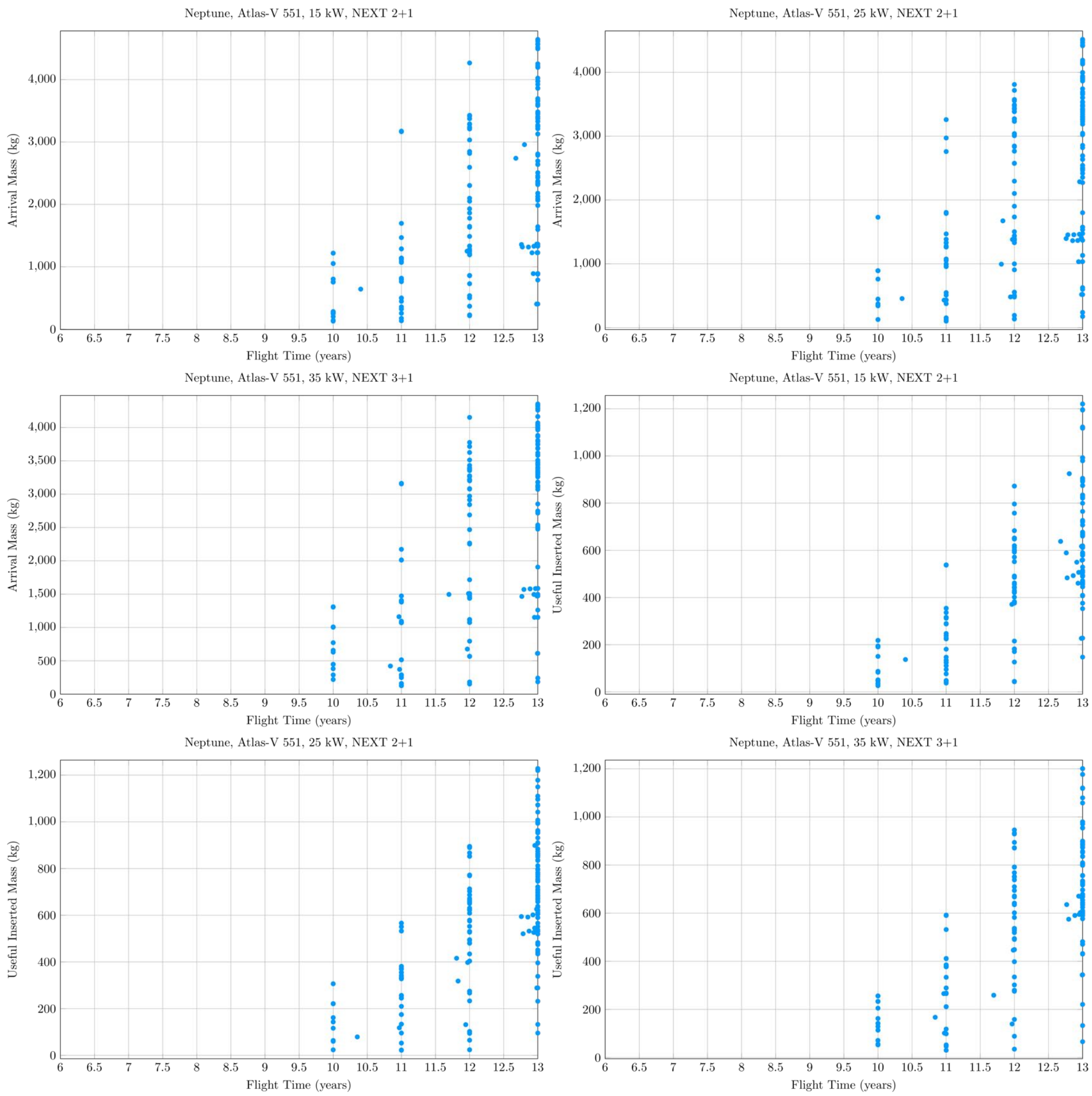

Figure 12. SEP trajectories to Neptune: Atlas V (551) Heavy with 15 kW, 25 kW and 35 kW SEP power

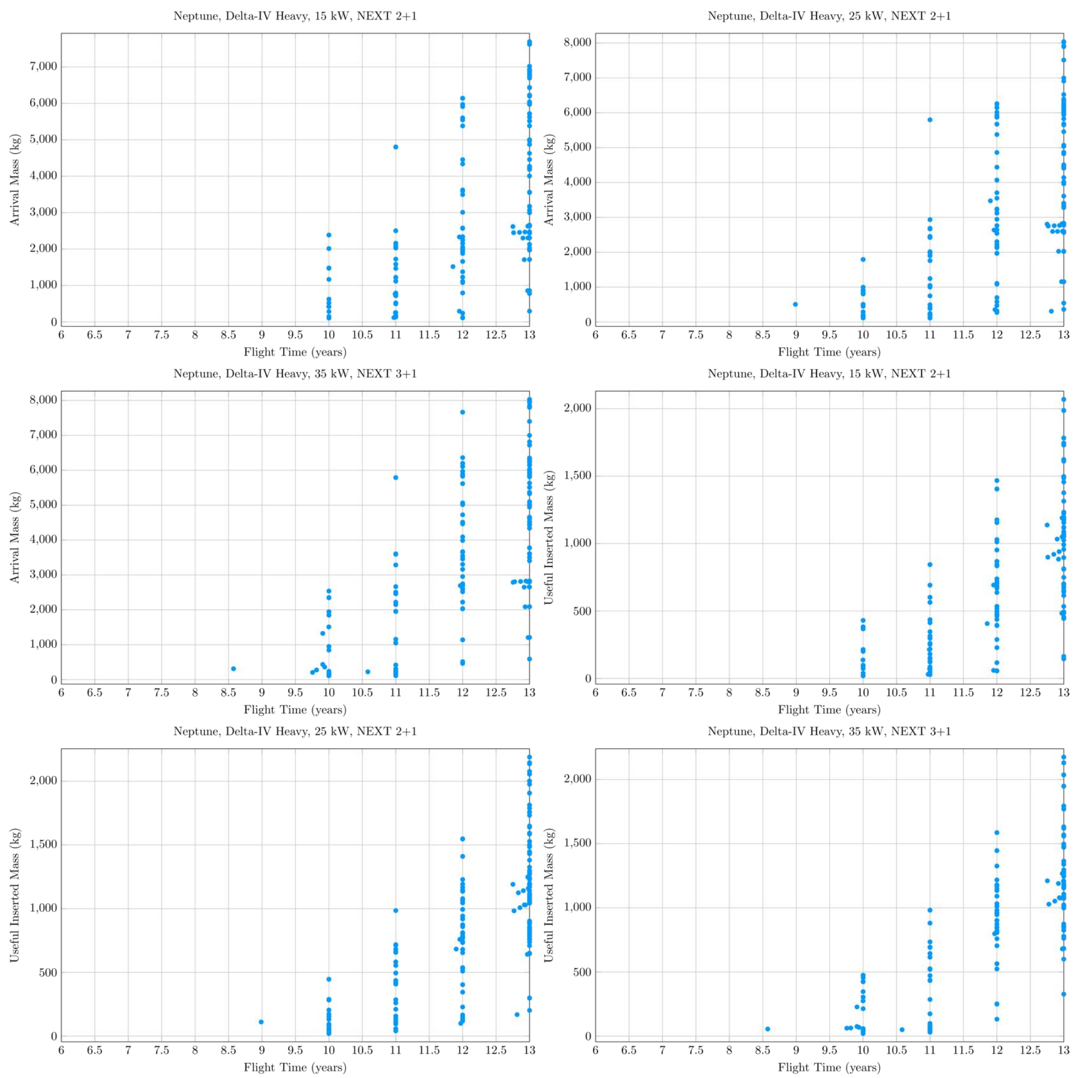

Figure 13. SEP trajectories to Neptune: Delta-IV Heavy with 15 kW, 25 kW and 35 kW SEP power

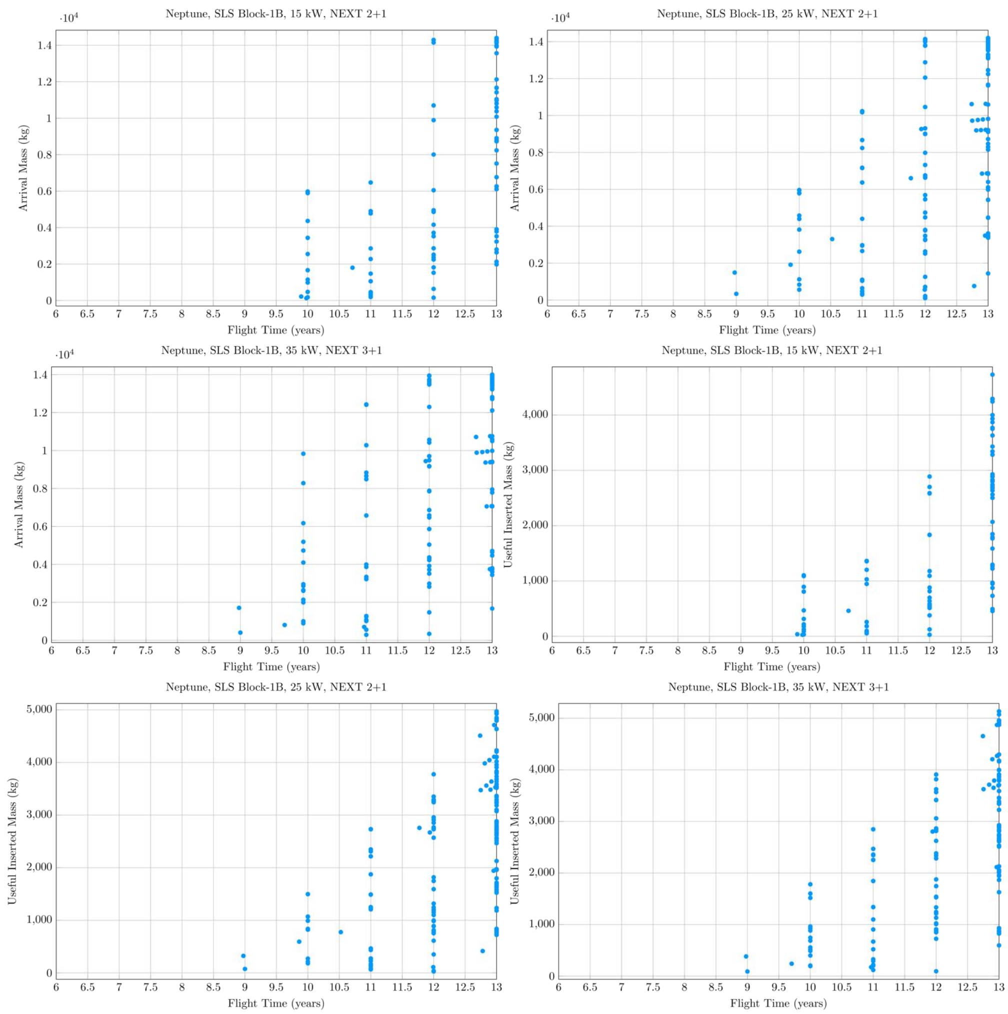

Figure 14. SEP trajectories to Neptune: SLS Block-1B with 15 kW, 25 kW and 35 kW SEP power

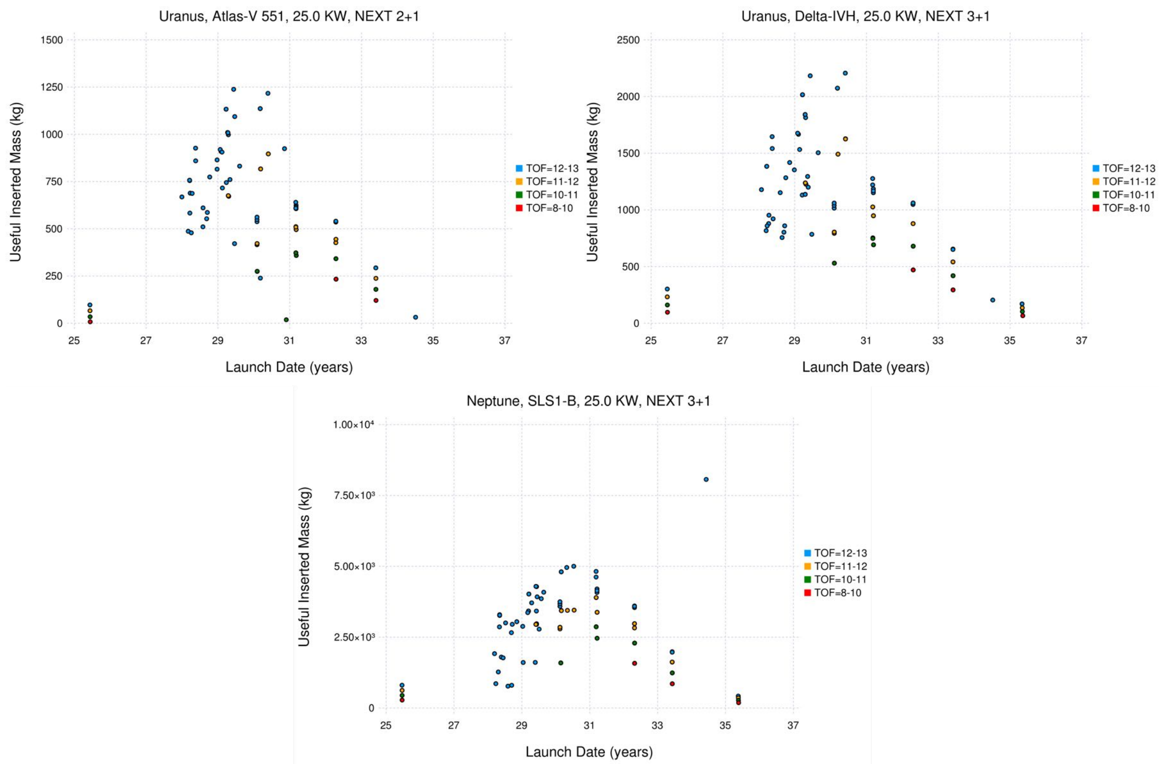

Figure 15. SEP trajectory options to Uranus: launch opportunities for 25 kW SEP power case

Dual Spacecraft, Single Launch Mission Options to Ice Giants

The large lift capability of the SLS-1B (or Delta-IV Heavy for smaller spacecrafts), coupled with fortuitous availability of gravity assists in Jupiters strong gravity well (for both Uranus and Neptune) and the high specific impulse of electric propulsion, allows a dual manifest to be considered, wherein two spacecraft are launched on a single launch vehicle, one destined for Uranus and one for Neptune. The two simplest options to consider are:

1. The two spacecraft are propelled by a single, large SEP stage, until one spacecraft separates, e.g., just before the Jupiter flyby, and continues with only chemical propulsion to one of the Ice Giants.
2. Two spacecraft, each with its own SEP stage, remain joined only until shortly after launch. They separate after Earth escape and use their respective SEP stages to propel them towards the two Ice Giants.

Examples of both of these (for assessing feasibility) are presented in this section. The case of departing on different launch asymptotes was not considered and will be considered in a future study. Many variations on the two simple options are possible, for example, performing a chemical deep-space maneuver directly after separation, using REP instead of SEP, separating before Earth flyby followed by Jupiter flyby etc. A full exploration of the dual-manifest trade space was beyond the scope of this study. The main aim of this work to asses feasbility of above stated, mission options.

The trifecta of SLS-1B, a Jupiter gravity assist, and EP permit large, flagship-class spacecraft to be inserted into orbit at each of the planets from a dual manifest launch. Removing any one of these three elements would likely disallow a pair of even floor missions. The early 2030s offer the last auspicious phasing of Jupiter for a dual Uranus-Neptune manifest for a number of decades. The first dual-manifest example presented here uses only a single gravity assist, at Jupiter, after launch. The objective is to insert as much useful mass as possible into orbit at each Ice Giant the sum total of useful inserted mass at each planet, under previously stated flight time constraints. In the second example, we present a case of minimizing the launch mass for a given useful inserted mass at each planet. These trajectories were computed in a semi-automated way: A grid search determined the general timeframe when opportunities of each type arise, and then further iterations were performed manually. The grid-search an Euclidean distance parameter with orthogonal components consisting of normalized launch V_∞ magnitude, normalized launch V_∞ declination, and gravity assist path sequence. Pair of interplanetary Uranus and Neptune trajectories with minimum distance parameter were selected for optimization in lockstep manner. The main prupose of this lockstep optimization procudre was to match launch conditions (date, V_∞ parameters) and if required, flyby date at Jupiter. Two example trajectories demonstrating feasibility of the Dual spacecraft single launch concept, are given in the next subsections.

Earth Launch Jupiter Ice-Giant: This trajectory assumes the two spacecraft remain joined until shortly before the Jupiter flyby, at which point they separate, with the Uranus-bound spacecraft keeping the SEP stage for further thrusting and the Neptune-bound spacecraft proceeding ballistically after a small targeting maneuver. In the design, mass can be traded between the two spacecraft. The result presented in Figure 16 is simply a representative point design in this option space. An 80-kW, 3500-kg, 9+1 NEXT SEP stage is assumed (a conservative mass estimate). High power SEP stages of up to 50 kW are feasible today and it is easy to see scalability to 100 kW in next 10 years. The high power is put to use after separation by continuing to provide some thrust (to the Uranus-bound spacecraft) after the Jupiter flyby to make up for the fact that the flyby occurs at the lower limit on the altitude. The larger SEP stage is also needed to provide the necessary thrust and acceleration.

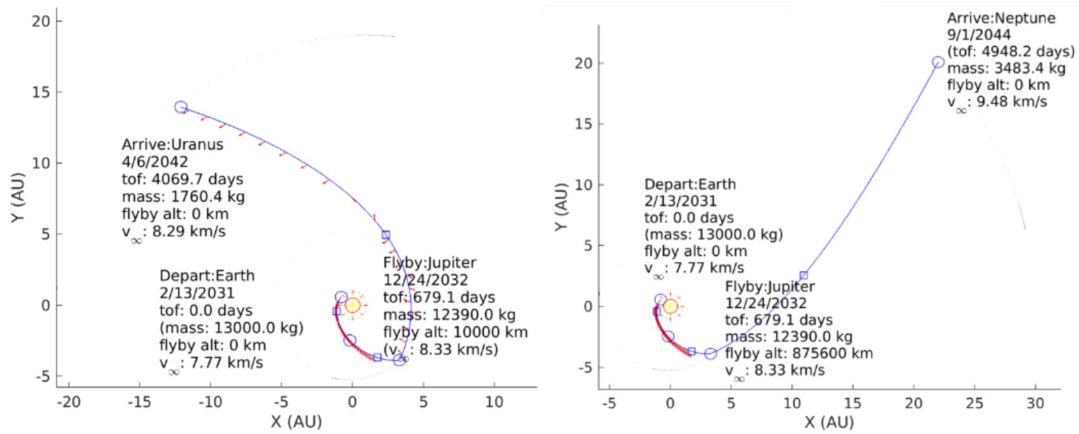

Figure 16. Uranus (left) and Neptune (right) part of Dual Manifest launch option A

Earth Launch Mars Jupiter Ice-Giant: The spacecraft separate just after launch and use their individual SEP stages for thrusting in the inner solar system. Both spacecraft follow similar trajectories with Mars flyby occurring on the same day. After Jupiter flyby, the Neptune spacecraft proceeds ballistically to Neptune, while the Uranus spacecraft continues to thrust for a short time. Note, that unlike the previous case, the Jupiter flybys do not occur on the same day. As with the previous case, mass can be traded between the two spacecraft. Furthermore, post orbit insertion masses can be increased (at the expense of increased SEP propellant load) as SLS-1B is capable of launching twice the combined masses of each spacecraft. The result presented in Figures 17 is a representative point design in this option space. Both spacecraft use the above described (see Table 4) 35-kW, 1000-kg, 3+1 NEXT SEP stage. This options benefits from the fact that the two SEP stages are identical to each other and hence might be cheaper than one big stage.

REP Mission Options to Uranus and Neptune

This section briefly summarizes high performing REP mission options to the Ice Giants. Given then the spacecraft could thrust all the way up to few days prior to orbit insertion, these trajectories are expected to have medium to low arrival relative velocity with respect to the target planet. This in turn results in substantial reduction in the orbit insertion ΔV and propellant.

Figure 18 highlights the interplanetary trajectory tradespace for REP missions to Uranus with up to 4 flybys, launching on Atlas V (551) and Delta-IV Heavy and with two different REP power levels (1.65 kW, 2.15 kW). The two REP power levels result in different total propellant (xenon) usage. All figures show Useful Inserted Mass as a function of launch date with colors representing interplanetary cruise time in years. Note, that colors are not consistent between figures.

Using a REP propulsion system before orbit insertion significantly increases the delivered useful mass into orbit when compared to pure chemical trajectory (Bi-Prop). It also results in increased launch flexibility allowing launches every year to Uranus for both class of launch vehicles. Specif-

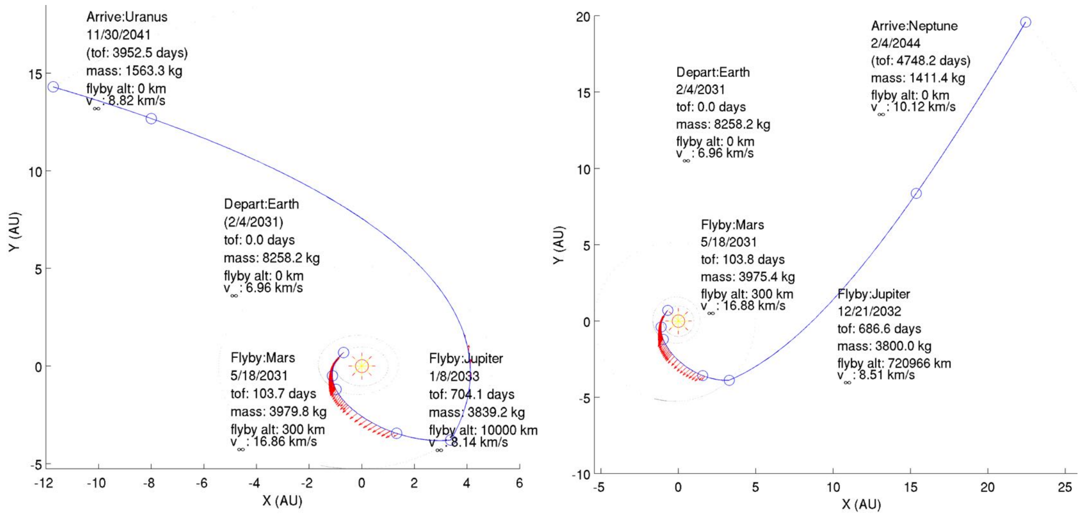

Figure 17. Uranus (left) and Neptune (right) part of Dual Manifest launch option B

ically, using a notional 1.65 kW REP system with Altas V (551) LV results in $\geq$ 1500 kg of useful inserted mass into Uranus with $\sim$11 years of interplanetary cruise time. Going to 25 kW REP stage results in small increase in delivered mass (on average). Note, that the high-power REP option comes with a reduced maximum allowable throughput due to XIPS thruster limitations. See REP assumptions for more details. Going from Atlas v (551) to the Delta-IV Heavy LV results in significant (almost 80%) increase in useful inserted mass at Uranus.

Figures 19highlights the interplanetary trajectory tradespace for REP missions to Neptune with up to 4 flybys, launching on Atlas V (551) and Delta-IV Heavy and with two different REP power levels (1.65 kW, 2.15 kW). As for the Uranus case, the two REP power levels result in different total propellant (xenon) usage.

Using a notional 1.65 kW REP system with Altas V (551) LV results in $\sim$1000 kg of useful inserted mass into Neptune orbit for a 12-13 years of interplanetary cruise time. Going to 2.15 kW REP stage results in small increase in delivered mass to $\sim$1100 kg. Note, that the high-power REP option comes with a reduced maximum allowable throughput due to XIPS thruster limitations. Going from Atlas v (551) to the Delta-IV Heavy LV results in significant (50% to 100%) increase in useful inserted mass at Neptune. It is possible using a 2.15 kW powered REP system, to insert $\geq$ 1500 km into Neptune orbit with 12 years of interplanetary flight time. Another consequence of using a REP trajectory is the significant reduction in orbit insertion ΔV. Figures 20 and 21 highlight this fact by showing the orbit insertion ΔV as function of the launch year. Only orbit insertion ΔVs for 1.65 kW REP power level trajectories are shown, as these results are representative of other power levels. Three things immediately stand out: 1) orbit insertion ΔVs for longer flight times, hybrid REP and Bi-Prop mission trajectories are significantly less when compared to equivalent Chemical or SEP mission trajectories, 2) orbit insertion ΔVs are smaller for Uranus when compared to Neptune, primarily due to Neptune trajectories having more time for breaking thrust before orbit insertion, and 3) orbit insertion ΔV is higher for launches using the higher performing Delta-IV Heavy LV. This is partially attributed to the fact that a high performing launch vehicle results in a larger launch mass for a given mission launch energy, resulting in less braking (and higher planet relative velocity) prior to target body orbit insertion.

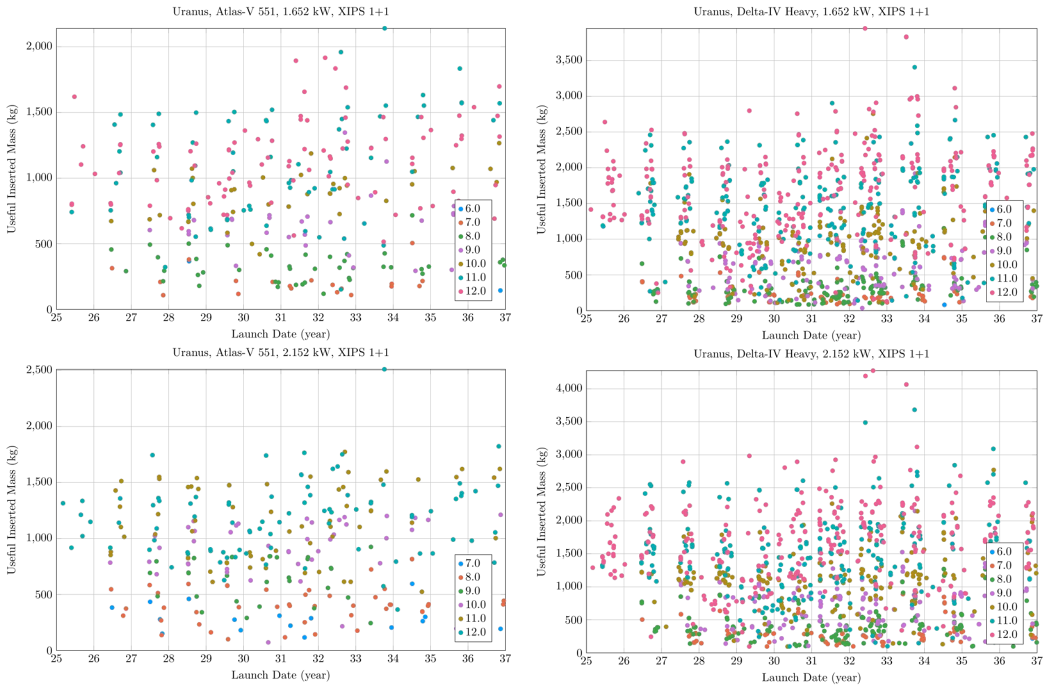

Figure 18. REP trajectory options to Uranus: Atlas V(551) LV (left), Delta-IV Heavy (right), 1.65 kW (top), 2.15 kW (top)

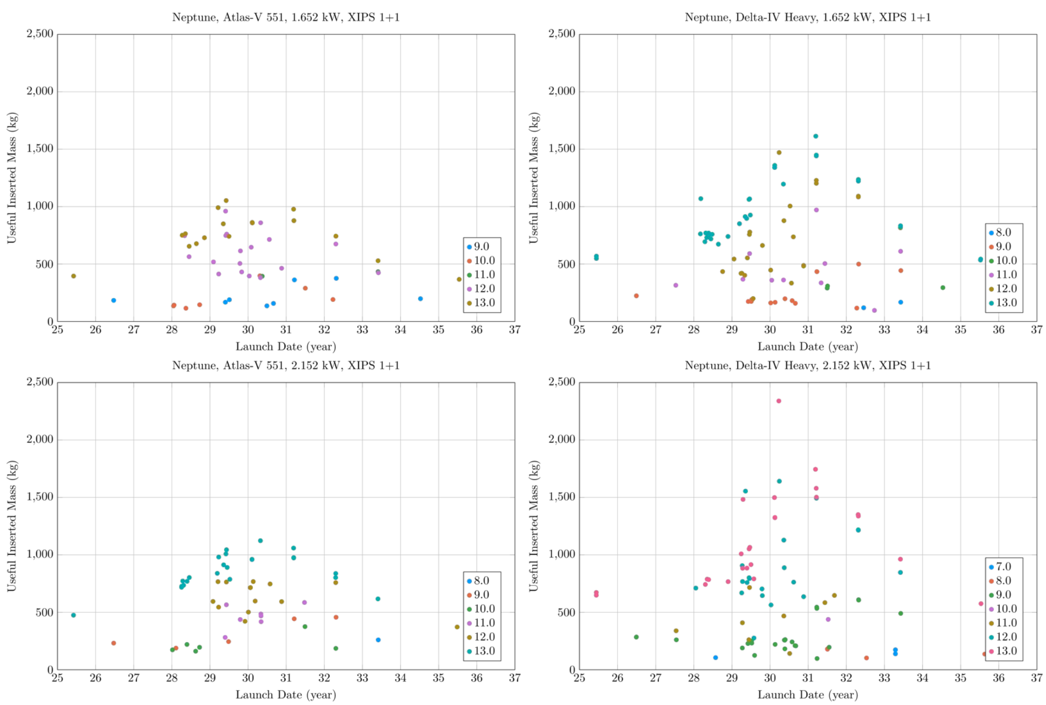

Figure 19. REP trajectory options to Neptune: Atlas V(551) LV (left), Delta-IV Heavy (right), 1.65 kW (top), 2.15 kW (top)

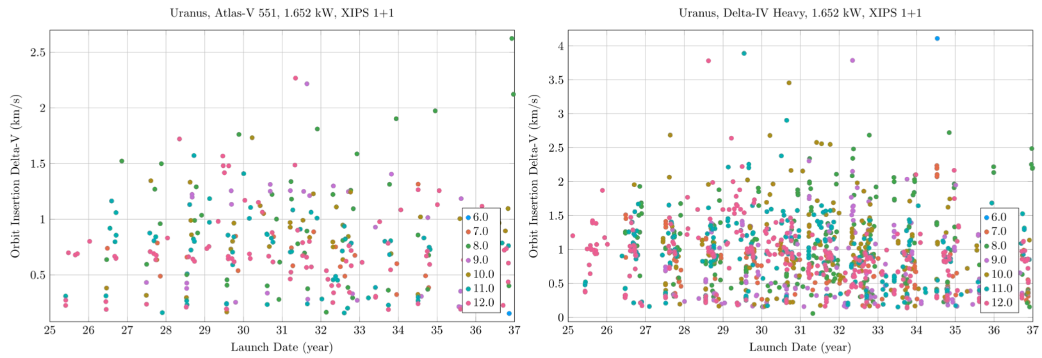

Figure 20. REP trajectory options to Uranus, Orbit Insertion ΔVs : Atlas V(551) LV left, Delta-IV Heavy (right)

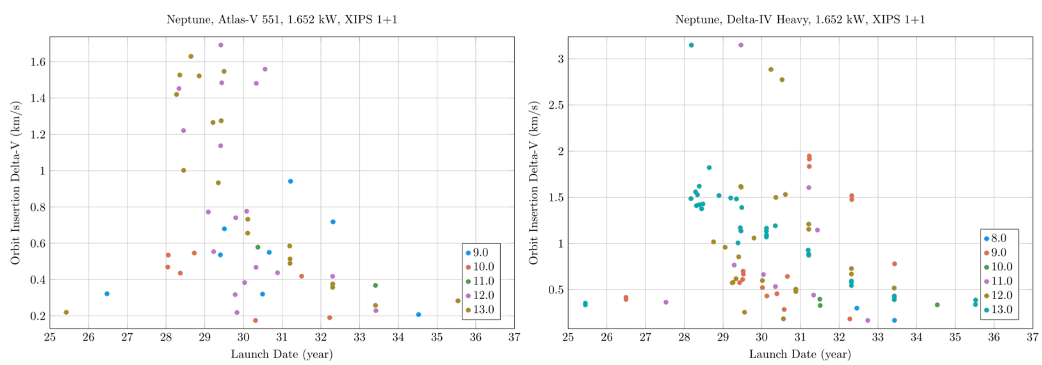

Figure 21. REP trajectory options to Neptune, Orbit Insertion ΔVs : Atlas V(551) LV left, Delta-IV Heavy (right)

CONCLUSIONS

A broad search for high performing trajectories for mission concepts to Uranus and Neptune, launching between years 2025 to 2037 was performed. High performing trajectory options were identified, which were then mapped to notional mission architectures to generate mission options. Launch vehicle options were evaluated, as were a variety of potential propulsion implementations. Tens of thousands of trajectories using various propulsion options, with up to four planetary flybys were investigated. The impact of using different launch vehicles (including SLS), on flight time, delivered mass, propellant throughput, and mission architecture were studied. Details of atmospheric probe coast, entry, and spacecraft orbit insertion at either of the two planets were evaluated. A procedure for computing dual spacecraft trajectories capable of delivering individual spacecraft to both planets on a single launch, was developed and exercised. Finally, trajectories using radioisotope electric propulsion were identified and their performance was evaluated.

The study finds that launches to an ice giant are possible any year within the considered timeframe (2025-2037), but there are significant variations in performance and available science targets. The availability of Jupiter gravity assist maximizes delivered mass to an ice giant resulting in preferential launch windows for Uranus missions in the 2030-2034 timeframe and a corresponding window of 2029-2030 for Neptune. In these favorable periods, purly chemical trajectories (with or without deep space maneuvers) could deliver ample mass for the Uranus missions studied in an 11-year flight time, using a launch performance capability similar to the Atlas V 551. Neptune trajectories utilizing solar electric propulsion (SEP) can deliver a similar mass to Neptune orbit in 13 years using launch performance capability similar to the Delta IVH. There are no all-chemical trajectories to Neptune, even using a Delta IVH, that yield a mission duration less than 15 years, a design target chosen to be consistent with Radioisotope Power System (RPS) design life and mission reliability. Significant science can be done during gravity assists at a gas giant, particularly if a Doppler Imager-type instrument is on board. If a Saturn flyby is preferred over the Jupiter gravity assist, only trajectories to Uranus are available in the time period studied, and launch must occur before mid-2028.

The use of SEP for inner solar system thrusting has the potential to significantly reduce flight times to Uranus and/or increase delivered mass. A variety of trajectories to Uranus and Neptune were evaluated considering a range of SEP power levels, assuming inclusion of an additional SEP flight element (referred to as a SEP stage). The SEP stage would carry solar arrays and ion thrusters and would be used in the inner solar system as far out as 6 AU, at which point solar power is insufficient to provide additional thrusting and the SEP stage would be jettisoned. SEP enhanced mission designs also see a slight preference in launch dates corresponding to availability of Jupiter gravity assists, but well-performing trajectories are possible in any year of the period

REP trajectories were found to follow trends similar to those of purely chemical trajectories but enjoyed grater mass to each of the target planets and significantly reduced orbit insertion ΔV. Further investigation of these trajectory options is recommended.

Early JPL studies suggested low-mass SEP stages are possible, which would provide significant performance enhancements at both Uranus and Neptune. The more detailed Team-X design suggested much higher masses, reducing the usefulness of SEP to Uranus. It may be valuable to perform a detailed assessment of an optimized SEP stage design for outer planet missions to confirm the optimal uses of SEP. This study found no trajectories that allow a single spacecraft to encounter both Uranus and Neptune. A single SLS launch vehicle could, however, launch two spacecraft, one to each ice giant.

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APPENDIX A: DOCUMENTED HIGH PERFORMING INTERPLANETARY TRAJECTORIES

This appendix documents a subset of high performing chemical and SEP trajectories for both Uranus and Neptune based on the assumptions outlined in Tables 1, 2 and 4. These are optimized to specific bounds so one can expect some improvement or degradation over these (especially SEP options) when applied to other mission / flight system constraints.

Appendix A.1: Trajectories to Uranus

Table 6. Chemical Trajectories to Uranus

Launch Date	C3	Path	Arrival Mass 551	Arrival Mass D4H	Arrival Mass SLS	Arrival V_∞	Arrival Declination	Useful Mass 551	Useful Mass D4H	Useful Mass SLS	TOF	OI ΔV	DSM
	km^2/s^2		kg	kg	kg	km/s	deg.	kg	kg	kg	years	km/s	km/s
20250601	51.3	3367	1409.9	2754.1	10739	11.41	72.65	458.3	895.2	3490.6	10	3.03	1.21
20250605	52.56	3367	1499.4	2930.2	11462.9	9.29	73.59	711.5	1390.5	5439.7	11	2.07	0.93
20250930	25.3	337	419.3	756.9	2745.4	7.04	77.69	271.2	489.6	1775.9	12	1.23	6.94
20260524	29.68	3367	1402.9	2572.3	9449.8	11.47	72.63	450.9	826.8	3037.5	9	3.06	2.78
20260808	27.33	3367	1507.7	2741.2	10001.6	7.45	74.68	927.1	1685.6	6150	11	1.37	2.72
20260817	26.3	337	453.4	821.2	2987.4	8.32	80.1	248.3	449.8	1636.3	10	1.69	6.62
20270612	30.72	3367	1360.2	2501.5	9217.8	8.71	76.98	704.5	1295.5	4773.9	10	1.84	2.81
20270715	52.56	337	674.4	1318	5156.2	8.44	82.35	363.2	709.9	2777	11	1.73	3.48
20271017	14.87	337	458.5	809.7	2847.2	8.13	79.49	257.9	455.4	1601.2	9	1.62	7.35
20280808	26.62	3367	512.7	929.6	3384.9	8.45	77.13	275.7	499.9	1820.2	9	1.74	6.21
20290908	48.51	337	511.4	993.8	3846.9	9.69	75.21	227.3	441.7	1709.8	10	2.24	4.64
20291124	12.8	323357	4167.7	7335.2	25631.3	13.1	47.99	931.2	1638.8	5726.6	11	3.9	0.44
20300724	17.13	332357	3377.3	5989.5	21204.1	11.55	47.13	1067.7	1893.6	6703.6	11	3.1	0.84
20300730	18.03	332357	3025.1	5374.8	19079.8	13.99	48.46	535.9	952.1	3379.7	10	4.39	1.13
20310222	30.84	32237	1824.8	3357	12374	7.61	71.94	1099.3	2022.3	7454.3	12	1.43	1.86
20310526	11.95	323357	4003.1	7036.7	24525.2	10.19	47.54	1634.9	2873.8	10016.3	11	2.46	0.63
20310716	52.56	3357	1547.7	3024.7	11832.6	14.05	48.6	269.8	527.2	2062.6	9	4.43	0.83
20310727	17.41	32357	3386.3	6008.9	21291.1	11.54	47.12	1073.4	1904.7	6748.8	10	3.09	0.81
20320503	28.5	3357	2826.6	5161.5	18896.8	8.47	47.8	1515.6	2767.5	10132.1	11	1.75	0.63
20320719	27.19	3357	2590.4	4707.2	17168	9.89	47.55	1115	2026.1	7389.6	10	2.32	1.01
20320726	28.44	3357	2365.4	4318.6	15808.3	12.15	47.59	659.1	1203.4	4405	9	3.4	1.21
20330609	29.88	3357	2118.6	3886.9	14287.5	8.84	51.66	1076.9	1975.7	7262.2	10	1.89	1.45
20330612	29.9	3357	2023.4	3712.5	13647.1	10.84	50.76	734.8	1348.2	4956.1	9	2.76	1.6
20330828	27.96	3357	2100.5	3828.1	13993.5	7.05	53.13	1357	2473	9040	11	1.24	1.62
20330829	27.29	3357	1794.7	3262.5	11902.4	12.91	50.16	419.9	763.3	2784.9	8	3.8	2.17
20340720	25.63	3357	692.2	1250.8	4541.4	10.58	50.76	263.6	476.3	1729.4	8	2.64	5.32
20340725	31.09	3357	722.8	1330.5	4907.8	8.62	51.75	379.4	698.4	2576.4	9	1.8	4.8
20341002	48.96	3347	1529.9	2977	11536.9	7.92	56.52	885.2	1722.5	6675.1	11	1.54	1.11
20341004	49.15	3347	1311.6	2553.6	9901.1	9.45	54.36	606.5	1180.7	4578	10	2.14	1.59
20351007	26.37	3347	1428.6	2588.1	9416.7	9.44	54.34	662.2	1199.7	4364.9	9	2.13	2.96
20351011	27.53	3347	1519.5	2764.8	10093.9	7.89	56.55	883.1	1606.8	5866.2	10	1.53	2.68
20351011	27.5	3347	1610.5	2929.9	10695.8	6.8	59.34	1071.2	1948.8	7114.1	11	1.16	2.5
20360215	44.55	32337	1562.4	2996.5	11477.7	10.72	40.69	580.6	1113.6	4265.6	11	2.7	1.37
20360821	49.61	3347	453.4	883.6	3430.2	8.07	56.28	257.1	501	1945	9	1.59	4.94
20360826	29.55	3347	501.9	919.9	3378.1	9.65	54.21	224.8	412	1513.1	8	2.22	6.07
20360923	57.26	337	476.1	932.4	3692.3	7.96	52.67	274.1	536.8	2125.9	10	1.55	4.27

Table 7. SEP Trajectories to Uranus with Atlas V (551): Part 1

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20250413	5607	3.95	33367	4073.6	8.99	76.81	2054.5	12	1.91	25
20250526	5700.8	3.09	3367	3709.2	7.75	74.55	2219.3	12	1.45	35
20250630	5610.7	3.91	337	3374.1	8.55	80.17	1813.7	11	1.74	35
20260614	4256	17.9	337	2875.8	8.61	80.15	1533	10	1.76	25
20260622	5421.5	5.68	337	3385.5	8.53	82.28	1825.4	12	1.73	35
20260710	5108.4	8.72	3367	3212.7	8.61	77.09	1686.8	11	1.8	25
20260726	4287.4	17.53	3367	2785.3	7.17	78.19	1788.4	12	1.25	15
20260812	4776.7	12.13	337	2960.1	8.32	79.69	1641.8	10	1.65	35
20260827	4982.3	9.99	3367	3378.3	8.19	80.04	1908.5	12	1.6	25
20270601	4323.3	17.12	3367	3021	8.77	76.96	1573.4	10	1.82	25
20270607	4372.8	16.55	337	3018.7	6.45	79.54	2102.3	12	1.03	25
20270701	5680.1	3.28	3367	3549.3	7.2	80.69	2271	12	1.26	35
20270730	4815.9	11.71	3367	3120.2	7.12	78.11	2015.5	11	1.24	35
20270801	4782.7	12.06	3367	3074.5	8.46	77.05	1672.9	10	1.71	35
20280528	4774.8	12.15	3367	3031.3	7.3	80.63	1918.2	11	1.29	35
20280813	3928.1	21.83	337	2379.8	7.1	81.57	1542	12	1.23	35
20280818	4757.2	12.33	3367	2996.9	8.22	80.03	1684.5	10	1.62	35
20280818	3511	27.23	337	2367.7	7.08	81.62	1536.7	12	1.22	25
20280902	4229.9	18.2	3367	2835.2	8.16	80.06	1606.4	10	1.6	25
20290614	4728.5	12.64	337	2958	8.53	80.04	1593.4	10	1.73	35
20290629	4244	18.04	337	2874.8	8.48	80.1	1560	10	1.71	25
20290712	4950.2	10.32	337	3364.3	8.37	73.26	1853.3	12	1.67	25
20290907	5420.7	5.69	327	2889.8	8.46	78.4	1573.1	11	1.7	35
20291106	5956.5	0.83	337	3363.1	7.95	73.67	1961.9	12	1.52	35
20300327	5373.2	6.14	3357	4235.7	10.13	46.63	1782.3	12	2.38	15
20300730	5746.1	2.69	32237	4190.8	9.94	68.42	1786	11	2.35	25
20300827	4819.8	11.67	337	3044.7	7.03	79.15	1988.3	11	1.21	35
20300908	4365.8	16.63	337	3009	6.18	81.05	2155.3	12	0.95	25
20301112	5684.7	3.24	32357	4576.3	10.86	46.88	1691.4	11	2.71	15
20301116	5691.2	3.18	32357	4243.2	9.01	46.48	2132.9	12	1.92	35
20310620	5952.3	0.86	33357	4495.1	8.26	47.81	2513.8	12	1.63	35
20310706	4270.3	17.73	337	2898.2	8.4	73.08	1590.6	10	1.68	25
20310723	5682.6	3.26	3337	4081.4	8.22	65.4	2295	12	1.62	25
20310729	5913.2	1.2	332237	4341.9	8.32	70.37	2408.4	11	1.65	15
20310729	5308.9	6.75	3337	3848.9	8.2	65.39	2169.9	12	1.61	15
20310906	4750	12.41	337	2968.9	8.11	73.57	1694	10	1.58	35
20310923	5926	1.09	332237	4263	8.12	70.69	2399.8	11	1.61	25
20311030	6016.7	0.3	332237	4118.4	7.99	71	2388.8	11	1.53	35
20320421	5710.5	3.01	32237	4379.8	6.52	75.09	3026	12	1.05	25

Table 8. SEP Trajectories to Uranus with Atlas V (551): Part 2

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20320422	5851.9	1.74	32237	4204.1	6.52	75.12	2905.1	12	1.05	35
20320423	5696.9	3.13	32237	4337.7	7.43	72.25	2702.1	11	1.34	25
20320424	5848.6	1.77	32237	4177.6	7.42	72.3	2603.1	11	1.34	35
20320425	5664.2	3.43	32237	4349.8	7.42	72.27	2711.1	11	1.34	15
20320427	5683.7	3.25	32237	4211.1	8.68	69.73	2187.5	10	1.83	25
20320429	5621.1	3.82	32237	4176.7	8.67	69.8	2204.9	10	1.79	15
20320429	5826	1.97	32237	4115.7	8.68	69.81	2172	10	1.79	35
20320706	4301.2	17.37	3357	3366.2	6.84	48.54	2246.3	12	1.15	15
20321207	4912.8	10.7	32237	3684.4	7.86	71.28	2173.9	10	1.49	25
20321215	5916.3	1.18	3357	3845.4	7.56	48.17	2357.3	11	1.38	35
20321231	5292.4	6.91	32237	3401.4	7.77	71.22	2029.2	10	1.46	35
20330118	4652.6	13.45	32237	3206	9.11	68.92	1588.2	9	1.96	25
20330728	4907.3	10.76	3357	3345.7	6.07	54.83	2421.2	12	0.92	35
20330802	4559.1	14.47	3357	3396.1	6.06	54.86	2461.1	12	0.92	25
20330804	4542.5	14.65	3357	3379.9	7.13	53.04	2180.7	11	1.24	25
20330815	4260.1	17.85	3357	3287.9	6.03	54.94	2390.3	12	0.91	15
20330816	4249	17.98	3357	3272.1	7.09	53.1	2121.1	11	1.23	15
20330817	4235.5	18.13	3357	3246.4	8.5	51.73	1756.7	10	1.72	15
20340125	5158.8	8.22	3357	3057.7	7.86	52.55	1802.7	10	1.49	35
20340713	4376	16.52	337	3043.9	6.24	66.44	2166.3	12	0.97	25
20340714	4215.6	18.37	3357	2737.3	7.05	61.54	1765.6	11	1.24	25
20340717	4322.1	17.13	337	2888.6	8.27	60.7	1591.5	10	1.67	25
20340915	3206.6	31.48	3347	2299.2	6.86	59.16	1529.9	12	1.16	15
20340923	5188.5	7.93	32337	3683.9	9.5	45.88	1716.7	12	2.12	35
20341012	5689.4	3.2	3347	3674.4	7.88	56.08	2161.6	11	1.49	35
20341208	3764.2	23.9	3347	2372.3	6.64	59.51	1618	12	1.09	15
20350905	4928.6	10.54	3347	3268.2	6.08	62.05	2364.6	12	0.92	35
20350906	4912.8	10.7	3347	3244.3	6.88	58.89	2154.9	11	1.16	35
20350908	4867.5	11.17	3347	3199.3	8	56.13	1852.3	10	1.54	35
20350914	4552.2	14.55	3347	3285.3	6.05	61.94	2382.4	12	0.92	25
20350917	4517	14.93	3347	3257.4	6.85	58.86	2171.2	11	1.15	25
20350923	4458.2	15.59	3347	3192.4	7.95	56.16	1861.3	10	1.52	25
20351006	4106.1	19.66	3347	2996.1	6.8	59.04	2007.8	11	1.14	15
20360305	5206.8	7.75	32337	4161.7	8.74	42.53	2176	12	1.81	25
20360714	4753.9	12.37	337	3037.4	6.22	58.06	2165.1	12	0.96	35
20360718	4727.4	12.65	337	3010.1	7.05	54.88	1961.4	11	1.21	35
20360719	4707.3	12.86	337	2968.8	8.21	52.08	1670.9	10	1.61	35
20360722	4360.8	16.69	337	2968.8	7.03	54.75	1918.5	11	1.24	25
20360725	4333.4	17	337	2947.8	8.2	52.01	1662.4	10	1.61	25
20360807	3896.1	22.23	337	2769.8	7	55.1	1814.6	11	1.2	15
20361023	4606.2	13.96	337	3124.2	7.8	44.47	1857.4	12	1.47	15

Table 9. SEP Trajectories to Uranus with Delta-IV Heavy: Part 1

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20250425	9063.7	7.37	33367	6771.3	8.93	76.84	3444.3	12	1.89	35
20250505	7543.2	17.41	33367	5877.7	8.88	76.87	3010.3	12	1.87	25
20250813	5544.3	33.63	337	4165.5	8.3	79.57	2286.8	11	1.68	25
20250818	4939.3	39.54	337	3863.1	8.3	79.5	2150	11	1.64	15
20250928	7302	19.15	3367	4716.7	8.71	73.81	2478	11	1.8	35
20260518	5128.2	37.63	3367	3960.1	9.38	73.55	1881.1	10	2.07	15
20260529	6604.7	24.5	3367	5147.9	9.33	73.58	2465.1	10	2.05	25
20260615	5960.2	29.88	3367	4506.5	11.34	72.71	1521.1	9	2.94	25
20260624	6971	21.63	337	4891.3	8.57	80.12	2619.1	10	1.75	35
20260803	5377.9	35.2	3367	4192.3	7.11	78.13	2710.9	12	1.23	25
20260807	4999.3	38.93	3367	3988.1	7.1	78.14	2583	12	1.23	15
20260812	5911.9	30.31	337	4230.3	8.3	81.79	2352.8	11	1.65	35
20260813	6955.6	21.75	3367	4955.2	10.89	72.75	1820.9	9	2.73	35
20260815	5599.9	33.12	337	4201.3	8.27	81.82	2316.3	11	1.67	25
20260817	7170	20.13	337	4488.2	7.17	81.09	2882.2	12	1.25	35
20260821	4966.7	39.26	337	3870.2	8.27	81.77	2161.6	11	1.64	15
20270531	4642.8	42.66	3367	3477.4	8.78	76.96	1808.6	10	1.83	15
20270623	6185.3	27.95	3367	4716	8.68	77.04	2486.6	10	1.79	25
20270711	5374.1	35.24	3367	3930.5	10.46	76.05	1561.6	9	2.53	25
20270809	5955.6	29.93	3367	4283.1	7.04	80.71	2793.1	12	1.21	35
20270810	5927.4	30.17	3367	4240.7	8.25	80.01	2374.2	11	1.63	35
20270816	5576.7	33.33	3367	4197.7	8.2	79.95	2335	11	1.65	25
20270816	5395.6	35.03	3367	4185.3	7.02	80.72	2735.7	12	1.21	25
20270822	7162.7	20.19	3367	5133.7	8.37	77.11	2827.4	10	1.67	35
20270822	4990.5	39.01	3367	3957.9	7	80.73	2591.9	12	1.2	15
20270823	4965.2	39.27	3367	3900.1	8.21	80.04	2197.6	11	1.61	15
20270905	6556.2	24.89	3367	4533.8	10.06	76.1	1928.9	9	2.35	35
20280624	7143.9	20.33	3367	5083.9	8.5	79.98	2749.4	10	1.72	35
20280714	8157.1	13.17	337	5787	8.39	77.04	3178.3	12	1.68	35
20280720	6412.2	26.06	337	4315.7	10.09	81.47	1826.9	9	2.37	35
20280723	5410.1	34.89	3367	3961.1	8.39	80.04	2176.8	10	1.68	25
20280807	3972.9	50.36	3367	2858.9	8.33	80.07	1584.7	10	1.66	15
20280820	5928.3	30.16	337	4243.6	8.22	80.44	2385.2	11	1.62	35
20280823	5618.6	32.95	337	4215.1	8.19	80.42	2350	11	1.64	25
20290707	7012.8	21.32	337	4945.5	8.45	80.09	2694	10	1.7	35
20290827	5882.4	30.57	337	4218.1	8.18	77.41	2386.3	11	1.6	35
20290831	5574.7	33.35	337	4196.1	8.14	77.44	2356.2	11	1.62	25
20290905	4990.3	39.02	337	3898.1	8.14	77.41	2215	11	1.59	15
20291012	5658	32.58	337	3659.7	9.54	79.11	1694.2	9	2.14	35
20291027	9284.3	6.04	323357	8047.1	10.95	46.91	2923.6	12	2.76	35
20291028	9151.9	6.84	323357	8350.3	10.95	46.91	3036.6	12	2.75	15
20291129	9736.5	3.38	33357	8239.2	10.77	46.84	3098	12	2.67	25

Table 10. SEP Trajectories to Uranus with Delta-IV Heavy: Part 2

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20300706	5790.6	31.39	337	4059.6	10.06	71.49	1727.6	10	2.35	35
20300721	9932.1	2.26	332357	8553.1	9.57	46.54	3940.3	12	2.15	25
20300728	6461.8	25.65	337	4391.5	10	75.34	1888.8	9	2.33	35
20300728	9687.8	3.66	32237	7307.4	9.95	68.42	3167.2	11	2.31	35
20300809	10103.3	1.3	332357	8378.8	9.49	46.55	3912.1	12	2.11	35
20300915	9729.7	3.42	332357	8040.3	13.62	48.18	1572.6	10	4.19	25
20301113	9707.4	3.55	32357	8062.8	10.83	46.83	2927.8	11	2.76	25
20301127	8996.1	7.79	32357	7823.6	8.96	46.48	3962.9	12	1.9	15
20301128	8963.1	7.99	32357	7768.3	10.8	46.84	2902.2	11	2.69	15
20310111	9054.5	7.43	322237	7486.4	7.74	71.54	4481.9	12	1.45	15
20310506	9628.8	4	332237	7628.8	7.39	72.27	4773.1	12	1.33	25
20310612	10194.4	0.79	332237	7904.1	7.28	72.57	5008.9	12	1.29	35
20310619	10165.4	0.95	332237	7731.9	8.47	70.04	4198.5	11	1.71	35
20310713	9178.3	6.68	33357	7768.3	9.93	47.55	3379.9	11	2.3	15
20310714	8201.6	12.87	32357	7131.1	11.61	47.16	2283.8	10	3.07	25
20310714	10061.5	1.53	332237	7647	8.36	70.27	4161	11	1.71	25
20310716	7041.1	21.1	337	4984.5	8.37	73.15	2747.9	10	1.67	35
20310719	8107.4	13.5	32357	7134.4	11.57	47.14	2299.7	10	3.05	15
20310731	6492.5	25.4	337	4418.2	9.96	71.45	1913	9	2.31	35
20320227	7753.8	15.92	32237	6216.7	7.6	71.85	3791.5	11	1.4	15
20320422	9656.4	3.84	32237	7629.5	6.52	75.06	5272.8	12	1.05	35
20320424	9644.1	3.91	32237	7550.5	7.42	72.22	4705.1	11	1.34	35
20320425	9441.8	5.1	32237	7319.1	8.67	69.77	3807.7	10	1.83	25
20320425	9620.4	4.05	32237	7651.6	7.41	72.29	4724	11	1.36	25
20320428	9625	4.03	32237	7388.5	8.68	69.71	3897.7	10	1.79	35
20320511	6771.1	23.18	32237	5288.5	8.63	69.89	2810	10	1.77	15
20320522	8962.9	7.99	33357	7432.9	7.4	52.88	4642.8	12	1.33	15
20320712	7178	20.07	3357	6040.3	12.25	47.6	1690.4	9	3.39	25
20320801	9564.9	4.38	33357	7887.5	7.14	53.03	5084.7	12	1.24	25
20320805	6480.4	25.5	337	4441.3	9.9	67.32	1941.5	9	2.28	35
20321205	7775.7	15.77	32237	6278	7.86	71.16	3702.5	10	1.49	25
20330105	7450.1	18.08	32237	5309.2	11.14	67.22	1861.6	8	2.84	35
20330124	7651.3	16.64	32237	5575	7.69	71.24	3360.3	10	1.43	35
20330126	7469.8	17.93	32237	5381.3	9.07	68.97	2680.8	9	1.94	35
20330810	7642.2	16.7	3357	5984.2	6.04	54.91	4344.9	12	0.91	35
20330814	7579.7	17.15	3357	5951.2	7.1	53.09	3854.5	11	1.23	35
20330817	7221.6	19.75	3357	5970.9	6.02	54.95	4343	12	0.91	25
20330818	7192.1	19.97	3357	5947.4	7.08	53.11	3858.7	11	1.23	25
20330821	7109.6	20.58	3357	5802.3	10.37	50.78	2340.8	9	2.49	25
20330822	6842.3	22.62	3357	5745.2	6.01	55	4184.3	12	0.9	15

Table 11. SEP Trajectories to Uranus with Delta-IV Heavy: Part 3

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20330824	6775.1	23.15	3357	5667.2	7.07	53.15	3684.6	11	1.22	15
20330827	6615.7	24.41	3357	5504.8	8.46	51.77	2995.8	10	1.71	15
20330906	6168	28.1	3357	5058.9	10.28	50.82	2074.7	9	2.45	15
20331206	3734	53.36	3237	2564.9	7.86	70.93	1512.2	9	1.49	25
20340726	7096.6	20.68	337	5043	8.24	60.72	2827.6	10	1.62	35
20340813	6587	24.64	337	4521.7	9.8	58.79	2008.6	9	2.24	35
20340913	5971	29.79	3347	4380.1	7.99	56.36	2540	11	1.53	35
20340916	5476.5	34.27	3347	4309.3	7.98	56.39	2503.1	11	1.53	25
20340917	5450.8	34.51	3347	4240.6	9.53	54.15	1966.8	10	2.13	25
20340920	5096.7	37.95	3347	4107.6	7.96	56.4	2390.3	11	1.52	15
20340922	5073.2	38.18	3347	4011.5	9.51	54.19	1867.7	10	2.12	15
20340929	8501.9	10.9	32337	6681.7	9.48	45.98	3125.8	12	2.11	35
20341024	7594.1	17.04	32337	6414.7	9.36	46.31	3056.2	12	2.06	15
20350916	4546.1	43.71	3347	3416.1	6.06	62.05	2477	12	0.92	15
20350924	7627.8	16.81	3347	5788.8	6.03	61.99	4206.3	12	0.91	35
20350925	7585.7	17.1	3347	5733.5	6.83	58.84	3831.1	11	1.14	35
20350928	7554.8	17.32	3347	5597.9	7.93	56.06	3270.8	10	1.51	35
20351002	5056.5	38.35	337	3957	7.9	52.84	2321.1	11	1.5	15
20351006	4882.1	40.13	337	3773.3	9.38	50.71	1791.2	10	2.07	15
20351006	7126.3	20.46	3347	5485.9	6.8	58.91	3641.7	11	1.16	25
20351012	6671	23.97	3347	5238.3	6	62.11	3818.5	12	0.9	25
20351014	7045.1	21.07	3347	5016.3	9.4	53.93	2374	9	2.08	35
20351031	5825.7	31.07	3347	4416.8	7.82	56.31	2619.9	10	1.47	25
20351112	4892	40.02	3347	3511.2	9.26	54.16	1699.5	9	2.02	25
20360307	8773.6	9.17	32337	7546.9	8.74	42.6	3948.4	12	1.81	15
20360308	8913.2	8.3	32337	7224.3	10.58	40.59	2810.1	11	2.58	35
20360404	7345.5	18.84	32337	5896.7	10.43	40.94	2354.6	11	2.52	15
20360803	7140	20.36	337	5075.5	8.17	52.03	2873.9	10	1.6	35
20360815	4849.7	40.46	337	3750.6	9.7	45.73	1694.4	10	2.2	15
20360927	5116.8	37.74	3347	3824.2	9.33	47.19	1830	10	2.05	25

Table 12. SEP Trajectories to Uranus with SLS-1B: Part 1

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20250516	6438.8	92.52	367	5094.2	10.51	67.87	2005.6	9	2.55	35
20250518	5705.2	97	367	4635.3	10.52	67.72	1783.2	9	2.61	25
20250608	15315.1	51.4	3367	14063.6	7.69	74.58	8473.4	12	1.43	25
20250609	15336.9	51.32	3367	13602.4	11.37	72.5	4453.6	10	3.01	25
20250609	15298.9	51.46	3367	13945.2	9.26	73.59	6748.5	11	2.02	25
20250613	15554.2	50.53	3367	13763	11.34	72.68	4648.2	10	2.94	35
20250618	12651.9	61.76	3367	11470	7.65	74.6	6945.1	12	1.42	15
20250622	11754.4	65.57	3367	10583.4	9.2	73.62	5171.1	11	1.99	15
20250705	15514.4	50.67	337	13448.2	8.52	79.94	7254.7	11	1.73	35
20250903	15510.6	50.68	337	13562.1	7.1	77.38	8786.4	12	1.23	35
20260526	10705.8	70.25	3367	9502.6	8.79	76.93	4932.6	11	1.83	15
20260528	6375.2	92.9	367	5033.8	9.35	69.05	2403.6	9	2.05	35
20260528	11850.7	65.15	3367	10645	7.36	77.99	6685.4	12	1.32	15
20260529	5911.9	95.71	367	4581.6	11.3	68.76	1558.5	8	2.92	35
20260530	5683.4	97.13	367	4616.1	9.35	68.85	2166.2	9	2.1	25
20260604	4640.4	103.91	367	3899.5	7.79	69.52	2321.9	10	1.46	15
20260622	15660.7	50.14	3367	14000	8.65	76.85	7306.2	11	1.82	25
20260622	15391.2	51.12	3367	14038.3	7.27	78.06	8907	12	1.29	25
20260628	15536.1	50.59	3367	13597.3	10.52	75.98	5345.7	10	2.56	35
20260703	13864.7	56.88	3367	12132.7	10.48	75.84	4700.9	10	2.59	25
20260824	15566.9	50.48	3367	13759.1	7.04	78.17	8976.6	12	1.21	35
20260825	15704.5	49.99	3367	13741.3	8.35	77.12	7587.3	11	1.67	35
20270608	9103.3	77.96	3367	7903.9	8.56	79.93	4241.6	11	1.74	15
20270609	10457.1	71.4	3367	9252.9	7.26	80.65	5880.6	12	1.28	15
20270611	5799.3	96.41	367	4468.9	10.12	70.68	1883.8	8	2.38	35
20270611	6215.6	93.86	367	4873.1	8.36	71.39	2688.6	9	1.67	35
20270612	5558.4	97.92	367	4483.5	8.35	71.17	2443.6	9	1.7	25
20270613	5151.9	100.52	367	4104.4	10.11	70.49	1697.3	8	2.43	25
20270615	4388.3	105.63	367	3645.2	8.34	71.38	2018	9	1.66	15
20270615	4616.4	104.07	367	3872.6	6.98	72.22	2542.3	10	1.19	15
20270624	14053.3	56.15	3367	12275.5	8.47	79.89	6579.4	11	1.75	25
20270625	14574	54.15	3367	13067.1	7.21	80.68	8349.7	12	1.27	25
20270804	10635.2	70.58	337	8941.6	9.97	81.6	3788.2	10	2.37	25
20270907	15602.3	50.35	3367	13506.4	8.14	80.06	7673.4	11	1.59	35
20270908	15692.3	50.03	3367	13795.6	6.95	80.75	9093.8	12	1.18	35
20270921	12609.7	61.94	3367	10528.3	9.67	79.24	4780.5	10	2.19	35

Table 13. SEP Trajectories to Uranus with SLS-1B: Part 2

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20280615	8393.5	81.6	337	7198	8.53	80.24	3878.1	11	1.73	15
20280624	5920.8	95.66	367	4589.8	7.64	74.63	2785.9	9	1.41	35
20280625	5535.6	98.06	367	4210.1	9.19	73.64	2060.3	8	1.99	35
20280625	5300.6	99.56	367	4245	7.61	74.42	2554.8	9	1.43	25
20280626	4927.7	101.99	367	3876.4	9.17	73.43	1871.2	8	2.03	25
20280626	10602.2	70.73	337	8848.8	10.15	78.89	3635.7	10	2.44	25
20280627	4459.2	105.14	367	3718.8	6.43	75.7	2594.3	10	1.02	15
20280628	3839.9	109.47	367	3101.9	9.16	73.62	1524.4	8	1.98	15
20280628	4204.8	106.9	367	3465.2	7.61	74.61	2109.1	9	1.4	15
20280628	13188.1	59.57	337	11421.1	8.45	80.22	6137.9	11	1.74	25
20280629	13533.3	58.18	337	12027.7	7.26	81.65	7648.3	12	1.28	25
20280718	15730.6	49.89	337	13667.9	8.4	80.35	7496.3	11	1.68	35
20280728	10889.2	69.42	337	9720	8.33	77.13	5386.7	12	1.66	15
20280917	15520.2	50.65	337	13595.9	7	81.67	8909.2	12	1.2	35
20281015	9930.6	73.89	3367	7883.5	9.64	81.26	3593.4	10	2.18	35
20290709	5523	98.14	367	4205.6	7.22	78.12	2685.1	9	1.27	35
20290710	5119	100.74	367	3804.1	8.6	77.07	2030.4	8	1.76	35
20290710	4921.2	102.04	367	3874.8	7.19	77.99	2458.8	9	1.29	25
20290711	4543.8	104.56	367	3496.2	8.57	76.9	1847.9	8	1.78	25
20290724	15513.3	50.68	337	13517.8	8.35	77.22	7463.5	11	1.67	35
20290801	13309.3	59.08	337	11587.8	8.3	77.22	6364.6	11	1.68	25
20290805	13434.4	58.58	337	11288.3	9.95	75.55	4895.1	10	2.31	35
20290811	7381.9	87.08	337	6230.8	8.22	77.33	3502.1	11	1.62	15
20290822	6728.2	90.82	337	5591.4	9.85	75.71	2463.2	10	2.26	15
20290921	15735.5	49.87	337	13767.9	6.97	79.47	9054.9	12	1.19	35
20291004	12126.9	63.97	337	10689.3	6.93	79.5	7056.3	12	1.18	25
20291013	8292.8	82.13	337	7172.7	6.91	79.59	4747.5	12	1.17	15
20291014	8355.2	81.8	337	6946.9	9.49	76.05	3243.5	10	2.11	25
20300601	14698	53.68	3357	13515.9	11.84	47.31	4128.8	11	3.18	15
20300605	15258.1	51.61	3357	14270.8	9.78	46.55	6361.3	12	2.23	15
20300626	6726.8	90.83	337	5544.5	10.13	71.6	2332.3	10	2.38	15
20300704	9403.5	76.46	337	7897.8	10.09	71.59	3345.8	10	2.37	25
20300709	13739.4	57.37	337	12231.4	7.18	75.62	7850.4	12	1.26	25
20300719	13420.9	58.63	337	11247.1	10.01	71.59	4826.1	10	2.33	35
20300725	4606	104.14	367	3304.3	8.37	80.04	1819.8	8	1.67	35
20300725	5008	101.46	367	3693.3	7.13	80.73	2383.9	9	1.24	35
20300726	4050.2	107.98	367	3020	8.33	79.95	1650.7	8	1.69	25
20300726	4436.6	105.3	367	3399.6	7.09	80.69	2183.2	9	1.25	25
20300729	15543.9	50.56	337	13551.9	8.31	73.52	7530.5	11	1.65	35
20300806	13346.8	58.93	337	11615.8	8.26	73.52	6415.4	11	1.67	25
20300927	15734	49.88	337	13778.2	6.93	76.24	9101.7	12	1.18	35

Table 14. SEP Trajectories to Uranus with SLS-1B: Part 3

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20310306	15110.6	52.15	32237	14094.4	8.89	69.66	7105	11	1.91	25
20310318	9884.8	74.11	357	9114.5	11.93	48.2	2732.6	10	3.23	15
20310717	15294.6	51.47	3357	14096	14.04	48.59	2564.7	9	4.34	25
20310720	15326.2	51.36	3357	14299.6	7.95	46.49	8331.3	12	1.52	25
20310722	12889	60.78	3357	11783.3	14.01	48.57	2162.6	9	4.32	15
20310723	15195.2	51.84	3357	14369.4	9.87	47.57	6308.5	11	2.27	15
20310723	15200.8	51.82	3357	14375.4	8.13	47.88	8187.7	12	1.58	15
20310802	15555.6	50.52	337	13585.4	8.26	69.53	7594.4	11	1.63	35
20310813	13773.6	57.24	337	11622	9.85	67.58	5121.9	10	2.26	35
20310915	15018.5	52.49	32357	13070	13.65	48.23	2634.5	9	4.12	35
20310916	15000	52.56	32357	13705.4	11.22	46.95	4622.7	10	2.94	25
20311001	15734.5	49.88	337	13771.1	6.89	72.54	9132.9	12	1.17	35
20320515	15390	51.12	32237	13353.3	7.36	72.4	8382.5	11	1.32	35
20320516	15355.8	51.25	32237	13260.8	7.35	72.49	8247	11	1.34	25
20320518	14833.3	53.18	32237	12300.7	8.6	69.86	6560.7	10	1.76	35
20320617	15258.3	51.6	3357	14106.4	10.07	47.55	5994.6	10	2.36	15
20320822	15052	52.36	3357	13938.1	8	47.9	8075.8	11	1.54	15
20320822	15219.5	51.75	3357	14117	6.69	48.67	9580.7	12	1.1	15
20320823	15358	51.24	3357	14046.1	11.93	47.52	4094.1	9	3.29	25
20320823	15284.9	51.51	3357	14141.8	9.7	47.56	6390.1	10	2.2	25
20320824	15386.3	51.14	3357	13878.7	11.94	47.57	4153.2	9	3.23	35
20320824	15298.6	51.46	3357	14181.4	6.68	48.67	9630.2	12	1.1	25
20320824	15305.8	51.43	3357	13900.4	6.68	48.67	9441.6	12	1.1	35
20320904	13737.4	57.38	3357	12608.2	12.87	50.2	3074.6	9	3.71	15
20330428	9224.1	77.35	357	8435.6	8.28	46.39	4708.6	10	1.64	15
20330430	11014.4	68.85	357	9670.4	12.03	47.42	2836.5	8	3.28	35
20330501	10477.7	71.31	357	9401.9	12.01	47.36	2695.7	8	3.33	25
20330507	13006.4	60.3	3357	11801.1	7.46	52.82	7321.3	11	1.35	15
20330508	13609.9	57.88	3357	12402.2	6.3	54.55	8768.8	12	0.99	15
20330713	15326.5	51.35	3357	13975.2	7.22	53.1	8921.8	11	1.27	25
20330716	14901	52.92	3357	13182.3	10.61	50.81	4989.2	9	2.65	25
20330726	15522.4	50.64	3357	14086.6	6.08	54.81	10189.4	12	0.92	25
20330930	15399.9	51.09	3357	13415	10.14	50.86	5635.1	9	2.39	35
20330930	15377.4	51.17	3357	13605.2	8.3	51.84	7563.9	10	1.65	35
20330930	15369.8	51.2	3357	13692.1	6.94	53.27	9032.2	11	1.18	35
20330930	15623.2	50.28	3357	13903.5	5.91	55.17	10226.6	12	0.88	35
20331001	14404.8	54.79	3357	12754.9	8.3	51.86	7004	10	1.68	25
20331014	8411.2	81.51	3357	7334.8	10.05	50.86	3126.9	9	2.35	15
20340607	9944.1	73.83	357	8609.6	10.13	47.58	3618.9	8	2.39	35
20340607	10235.3	72.44	357	8893.4	8.32	47.85	4930.8	9	1.66	35
20340608	9394.4	76.5	357	8072.8	12.53	47.65	2127.4	7	3.53	35

Table 15. SEP Trajectories to Uranus with SLS-1B: Part 4

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20340608	9457.2	76.19	357	8399.6	10.11	47.54	3474	8	2.43	25
20340608	9750.9	74.76	357	8684.3	8.31	47.83	4759.5	9	1.69	25
20340608	9916	73.96	357	8841.9	6.93	48.53	5781.7	10	1.2	25
20340609	8913.5	78.92	357	7862.4	12.5	47.58	2020.7	7	3.59	25
20340609	8911.1	78.93	357	8148.9	8.31	47.83	4526.6	9	1.65	15
20340609	9072.9	78.11	357	8312.1	6.93	48.5	5490.7	10	1.18	15
20340609	9185.8	77.54	357	8421.5	5.86	49.67	6224.6	11	0.86	15
20341012	15311.2	51.41	3347	13884.8	7.88	56.45	8164.2	11	1.5	25
20341012	15357.9	51.24	3347	14111.7	6.79	59.27	9466.6	12	1.13	25
20341012	15299.4	51.45	3347	13830.1	6.79	59.29	9278	12	1.13	35
20341013	15577.5	50.44	3347	13850.6	7.88	56.55	8147.8	11	1.49	35
20341016	15170.5	51.93	3347	13053.9	9.39	54.2	6190.3	10	2.07	35
20341021	12576.9	62.07	3347	11441.5	6.77	59.39	7693.5	12	1.13	15
20350714	7901.9	84.22	357	6576.7	7.22	53.12	4198.6	9	1.27	35
20350714	8164.3	82.82	357	6827.8	6.13	54.95	4914.7	10	0.94	35
20350715	7557.9	86.11	357	6239	8.67	51.78	3293.2	8	1.79	35
20350715	7399.4	86.99	357	6347.9	7.21	53.09	4015.3	9	1.3	25
20350715	7659.6	85.55	357	6600.8	6.13	54.88	4716.6	10	0.96	25
20350716	7047.2	88.98	357	5736.4	10.63	50.84	2210.5	7	2.61	35
20350716	7049.8	88.96	357	6004.2	8.66	51.73	3131.3	8	1.82	25
20350716	6751.2	90.68	357	6002.2	6.11	54.88	4326.3	10	0.93	15
20350716	6964	89.45	357	6212.8	5.29	57.17	4838.4	11	0.72	15
20350717	6545.5	91.89	357	5500.3	10.61	50.78	2083.6	7	2.65	25
20350717	6132.6	94.36	357	5386.6	8.66	51.73	2851.1	8	1.78	15
20350718	5606	97.62	357	4862.2	10.6	50.8	1882.2	7	2.6	15
20350721	10098.8	73.09	337	8893.2	7.05	55.04	5796.7	12	1.21	15
20350804	14170.2	55.69	337	12661.6	7.01	55.09	8287.3	12	1.2	25
20350822	15533.1	50.6	337	13604.2	8.1	52.54	7777.5	11	1.57	35
20350828	13853.1	56.92	337	12126.4	8.08	52.47	6862.7	11	1.6	25
20351022	15478.5	50.8	337	13589.4	6.77	56.02	9133.5	12	1.13	35
20351205	7437.9	86.77	3347	5465.2	9.15	54.2	2687.8	9	1.98	35
20360826	15754.2	49.81	337	13786.4	8.07	48.18	7911.3	11	1.56	35
20360901	14371.7	54.92	337	12213.1	9.62	45.86	5583.7	10	2.17	35
20360901	13863.5	56.88	337	12127.3	8.05	48.02	6890.1	11	1.59	25
20360901	11369.8	67.26	337	10202	8.03	43.52	5887.7	12	1.55	15
20360911	11593.2	66.27	337	9882.5	9.57	45.92	4474.3	10	2.19	25
20360925	8392.2	81.61	337	6735.9	11.67	44.47	2074.6	9	3.16	25
20361012	4119.2	107.49	337	3023.1	7.92	53	1768.3	10	1.51	15
20361025	15603.5	50.35	337	13697.6	6.76	51.67	9222.5	12	1.12	35
20361105	12475.8	62.5	337	11042	6.74	51.75	7454.2	12	1.12	25
20361116	7524.1	86.29	337	6413.9	7.73	49.02	3846.8	11	1.44	15

Appendix A.2: Trajectories to Neptune

This section highlights chemical and SEP trajectories to Neptune.

Table 16. Chemical Trajectories to Neptune

Launch Date	C3	Path	Arrival Mass 551	Arrival Mass D4H	Arrival Mass SLS	Arrival V_∞	Arrival Declination	Useful Mass 551	Useful Mass D4H	Useful Mass SLS	TOF	OI ΔV	DSM
	km^2/s^2		kg	kg	kg	km/s	deg.	kg	kg	kg	years	km/s	km/s
20261112	24.86	322238	1932	3482.9	12616.6	14.57	14.08	346.3	624.2	2261.2	13	4.37	2.11
20261213	52.56	322238	1340.7	2620.2	10250.2	14.4	14.1	251.7	491.8	1924.1	13	4.27	1.29
20280607	22.53	323358	3274.6	5870	21118.7	14.75	8.97	559.7	1003.3	3609.5	13	4.47	0.58
20290328	26.65	33458	2811.3	5098.2	18565.1	14.43	8.48	522.8	948.1	3452.5	12	4.29	0.78
20290328	26.49	33458	3063.3	5552.2	20209	12.65	8.4	862.1	1562.6	5687.5	13	3.38	0.52
20300607	52.56	3358	1250.9	2444.5	9563.1	12.81	8.98	340.5	665.3	2602.8	12	3.45	1.51
20300611	52.56	3358	1214.1	2372.7	9282	14.7	8.94	210.3	411	1607.8	11	4.44	1.6
20300802	11.53	33458	695.1	1221.1	4250.7	10.72	8.36	281.1	493.8	1719	13	2.48	6.23

Table 17. SEP Trajectories to Neptune with Atlas V (551)

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20290506	5812.1	2.1	33358	4494.4	12.97	8.98	1220.4	13	3.46	15
20290508	5861	1.66	33358	4462.1	12.95	8.98	1178.4	13	3.52	25
20290522	5892.2	1.39	33358	4260.9	12.89	8.98	1176.6	13	3.42	35
20300411	4854.6	11.31	3358	3320.1	11.49	9.05	1201.1	13	2.77	35
20300417	4664.3	13.33	3358	3381.3	11.47	9.05	1228.3	13	2.76	25
20300427	4247.8	17.99	3358	3268.3	11.42	9.05	1196.2	13	2.74	15

Table 18. SEP Trajectories to Neptune with Delta-IV Heavy

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20261025	7811	15.52	322238	6522.2	14.67	14.07	1186.3	13	4.34	25
20261025	7837.2	15.34	322238	6352.3	14.68	14.07	1154.2	13	4.34	35
20261029	7500.9	17.71	322238	6439.5	14.66	14.07	1176.4	13	4.33	15
20271130	7483.9	17.83	3358	5855	14.25	8.85	1185.9	13	4.11	35
20280407	8994	7.8	33358	7622.4	14.37	8.48	1497.3	13	4.18	15
20280407	9836.8	2.8	33358	7980.4	14.37	8.48	1568.6	13	4.18	35
20280412	9713.7	3.51	33358	8040.1	14.34	8.48	1591.9	13	4.16	25
20290319	7111.3	20.57	33458	6202.5	12.69	8.4	1782.8	13	3.33	15
20290320	7086	20.76	33458	6143.1	14.48	8.49	1176.2	12	4.23	15
20290505	9844.5	2.76	33358	7905.2	12.97	8.98	2146	13	3.46	25
20290505	9917	2.35	33358	7849.9	12.97	8.98	2130.5	13	3.46	35
20290513	9796.2	3.04	33358	7665.5	14.86	8.94	1325.7	12	4.44	35
20291023	7346.3	18.83	32358	5675.9	13.98	8.99	1229	12	3.97	25
20300425	7592.8	17.05	3358	5954.6	11.44	9.05	2174.9	13	2.74	35
20300428	7365.6	18.69	3358	5978.6	11.42	9.05	2189.5	13	2.74	25
20300429	7511.8	17.63	3358	5885.1	13	8.98	1586.2	12	3.48	35
20300430	7321.8	19.01	3358	5928.4	13	8.84	1548.2	12	3.55	25
20300505	6735.3	23.46	3358	5625.2	11.39	9.06	2069.3	13	2.72	15
20300510	6496.6	25.37	3358	5383.1	12.95	8.98	1467.5	12	3.45	15
20310203	3892.2	51.36	3458	2832.7	10.12	8.37	1287.7	13	2.18	25
20310204	4068.1	49.2	3458	2745.8	11.38	8.37	1012.5	12	2.72	35
20310204	4128.2	48.49	3458	2800	10.12	8.38	1272.5	13	2.18	35
20310205	3384.7	58.02	3458	2629.9	10.11	8.37	1197	13	2.18	15
20320316	3415.4	57.59	358	2091.6	9.17	9.37	1091.5	13	1.82	35
20320318	3071.7	62.5	358	2023.1	9.16	9.35	1057	13	1.81	25

Table 19. SEP Trajectories to Neptune with SLS-1B

Launch Date	Launch Mass	C3	Path	Arrival Mass	Arrival V_∞	Arrival Declination	Useful Mass	TOF	OI ΔV	P0
	kg	km^2/s^2		kg	km/s	deg.	kg	years	km/s	kW
20261215	15073.4	52.29	322238	13671.1	14.39	14.09	2677.3	13	4.19	35
20280402	15244.3	51.66	3358	13880.9	13.65	8.76	3240.2	13	3.8	25
20280405	15221	51.74	3358	14381.9	14.39	8.48	2813.9	13	4.19	15
20290216	15218.8	51.75	3358	14147.6	14.66	8.49	2583.4	12	4.33	15
20290501	15169.7	51.93	33458	13994.2	12.5	8.39	4177.3	13	3.24	35
20290504	15214.2	51.77	3358	14167.5	12.49	8.39	4244.1	13	3.23	15
20290506	15330.6	51.34	3358	14116.1	14.23	8.36	2767.6	12	4.18	25
20290506	15358.5	51.24	3358	13952.3	14.22	8.47	2850	12	4.1	35
20290506	15169.3	51.93	3358	14012.2	12.48	8.39	4205.2	13	3.22	25
20300325	15413.7	51.04	3358	13938.8	11.57	9.07	4973.5	13	2.8	25
20300331	12115.6	64.02	3358	10977.2	11.54	9.07	3933.3	13	2.79	15
20300404	11021.8	68.81	3358	9889.2	13.14	9	2588.9	12	3.54	15
20300611	15346.7	51.28	3358	13612.3	11.25	9.06	5135.5	13	2.66	35
20300613	14463.8	54.57	3358	12431.5	14.68	8.94	2255.2	11	4.34	35
20300614	13697.9	57.53	3358	12052.9	12.79	8.85	3294.2	12	3.44	25
20300619	11854.6	65.14	3358	10234.3	14.65	8.94	1873.7	11	4.33	25
20300628	7537.3	86.22	3358	6472.6	14.59	8.93	1202.1	11	4.3	15
20310208	11239.1	67.84	3458	10186.1	12.88	8.29	2733.1	11	3.49	25
20310208	11518.3	66.6	3458	10459.8	11.37	8.24	3776.3	12	2.77	25
20310208	11893.4	64.97	3458	10565.8	11.36	8.37	3909.5	12	2.71	35
20310208	11639.4	66.07	3458	10590.5	10.1	8.37	4826.8	13	2.18	25
20310208	12094.6	64.11	3458	10758	10.1	8.37	4901.5	13	2.18	35
20310209	11591.2	66.28	3458	10281.2	12.87	8.41	2847.7	11	3.41	35
20310209	11106.4	68.43	3458	10373.8	10.1	8.36	4730.6	13	2.17	15
20310210	11131.5	68.32	3458	9834.5	14.69	8.5	1780.5	10	4.35	35
20310224	6644.1	91.29	3358	5888.8	14.61	8.49	1088.9	10	4.31	15
20320324	8395	81.6	358	7072.9	9.14	9.35	3704.9	13	1.81	35
20320325	7891.4	84.28	358	6578.5	11.57	9.07	2346.9	11	2.8	35
20320325	8182.1	82.72	358	6864.2	10.24	9.19	3058.9	12	2.23	35
20320325	7893.1	84.27	358	6838	9.14	9.34	3583.9	13	1.81	25
20320326	7478.7	86.54	358	6171.4	13.18	9	1600.9	10	3.57	35
20320326	7414.4	86.9	358	6370.4	11.57	8.92	2216.4	11	2.86	25
20320327	6793.2	90.44	358	6046.8	10.23	9.17	2699.8	12	2.23	15
20320327	7005.9	89.21	358	6258.8	9.13	9.33	3283.6	13	1.8	15
20320410	3597.1	111.22	3358	2855.8	11.5	9.07	1031	11	2.77	15
20330503	5071.6	101.05	358	3760.2	8.56	11.35	2129	13	1.6	35
20330504	4826.5	102.66	358	3515.1	9.52	11.04	1745.1	12	1.95	35
20330504	4521.3	104.72	358	3480.5	8.55	11.34	1972.3	13	1.6	25